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FINAL REPORT

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David Taylor Naval Ship R&D Center
Annapolis, Maryland 21402

MODULAR LOW-PRESSURE PLASMA SPRAY SYSTEM FOR COATING OF MACHINE ELEMENTS

Contract No. N00167-84-K-0060

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A small plasma spray gun has been designed and fabricated with the goal of achieving simplicity and economics of construction and operation, both in air and within a reduced pressure environment. This gun, which is designed to be highly "operator-forgiving" is made using ordinary shop equipment and inexpensive materials and does not require critical dimensioning.

MODULAR LOW-PRESSURE PLASMA SPRAY SYSTEM

ABSTRACT

A small plasma spray gun has been designed and fabricated with the goal of achieving simplicity and economics of construction and operation, both in air and within a reduced pressure environment. This gun, which is designed to be highly "operator-forgiving" is made using ordinary shop equipment and inexpensive materials and does not require critical dimensioning.

A discussion is presented on gun design and operational criteria and how the present micro-gun meets established requirements for a wide range of plasma spraying conditions.

I. INTRODUCTION

Vacuum plasma spraying (VPS) is able to produce metallic coatings which are very dense and adhere well to the substrate. It has been our goal in this NAVSEA/NSRDC-sponsored program to design and construct a modular VPS system for the application of metal alloy coatings to rods and shafts. Of special importance has been the miniaturization of the plasma gun, which permits the operation of the system using plasma gas flow levels which are significantly below those employed in full-sized systems. This reduced gas flow enables us to employ much smaller mechanical pumps, yielding a less complex system and operating at significantly lower cost-per-thickness of applied coating.

Of central importance here is the design of a small, low power plasma gun, leading to a high Deposition Efficiency (DE). A novel spray gun has thus been designed, constructed, and tested, and fulfilling the following requirements: a high DE for a wide range of metallic and ceramic powders;

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operation at reduced power levels (e.g., <30 kW); employing a low plasma gas through-put (e.g., <80 SCFM; 37.7 SLPM). It is furthermore required that this gun will operate at both atmospheric and reduced pressures (to as low as 10 torr).

On the basis of the above requirements and, further, attempting to maintain costs at a low level, a gun has been designed which is essentially "expendable" - that is, a gun which costs about as much to fabricate as it costs to replace a set of electrodes in a normal 40 kW plasma gun system.

Before discussing VPS, it will be of interest to examine ordinary plasma spraying in ambient atmosphere. As depicted in Fig. 1, the powder is inserted as indicated, at a rate somewhat less than 10 lbs/Hr. The particles in a normal 40 kW plasma flame can reach velocities of 500 M/s and the temperature at the nozzle exit is in excess of 10,000°C. In general, the plasma flame is turbulent, introducing oxygen up to 30 volume percent.

It is believed that both particle velocity and temperature can be substantially increased by reducing ambient pressure. This is shown in Fig. 2, where the centerline flame temperature is plotted versus spray distance for pressure varying from 760 torr to 40 torr. It is seen that a distance of 150mm from the exit nozzle, when the pressure is reduced from 760 to 40 torr, the plasma temperature increases from about 540°C to 3600°C, respectively. This very large increase in flame temperature will, of course, enhance particle melting and, thus, substantially improve DE.

In addition to increased temperature operation, VPS has a substantially reduced oxygen content within the chamber. It is important to note that the oxygen partial pressure is indeed low due to the very high rate of introduction of the Ar/H_2 plasma gas. This constant flushing at high temperatures enables the substrate to be maintained at high temperatures (red hot for steel substrates) yielding the formation of a dense, well adhered and essentially oxygen-free coating. High performance nickel-based aircraft bond-coat alloys are plasma sprayed at low pressures to achieve the high density and metallurgical bond required for protection in extreme environments.

II. GUN DESIGN AND OPERATION

In the design of a plasma spray gun it is imperative to avoid leakage of water coolant into the plasma gas chamber. If this does occur failure will be catastrophic. O-ring seals are thus critical and great care must be taken to assure tight seals which will not fail during gun operation. Fig. 3 shows the various critical seals for a typical 40 kW plasma spray gun. In the present modular gun there are no critical O-ring seals to contend with. It is of importance to note that the electrodes and insulators which comprise the gun are sealed, modular units, which can be assembled in only one way. This makes it straightforward to construct the gun properly and easily, with no error in fabrication. In fact, the parts that comprise the gun are simply constructed and can be fabricated and assembled by a typical machine shop. It is to be noted that multiple plasma gases can be employed, making this gun very flexible for a wide range of powder feed-stocks and applications.

Before discussing the NAVSEA MICRO-PLASMA SPRAY GUN ("μ-gun"), it is appropriate to review basic gun design and operation. In Fig. 1 is shown the schematic of an external feed plasma spray electrode-powder feeder configuration that might be employed for vacuum plasma spray operations. Note that the exit region of the anode is flared; A. The flame expands on exiting due to the reduced ambient pressure within the chamber. (It is to be noted that the present μ-gun has a straight nozzle - no deficiency in operation was noted with this nozzle geometry.)

In operation, an initiating arc is struck between the cathode and the anode. Both the electrodes must receive effective water cooling to achieve reasonable operational thermal efficiencies. The plasma gas is introduced in a direction either normal to the electrode axis or almost tangentially to the anode, thereby creating a vortex action. This latter flow forces the arc to rotate within the anode bore, enabling arc breakup. Arc residency times on one area location on the bore are thus shortened, decreasing the chance of heat buildup at one spot and, thus, burn-through.

The cathode is constructed of thoriated tungsten, due to the need to have low erosion refractory properties and, also, a low electron work function. Although considerable study (both fundamental and empirical) have gone into cathode design, with time the cathode tip becomes essentially flat. In the design of the present μ-gun, the cathode is inexpensive 1/8-inch diameter tungsten welding rod, with a flat, unfinished tip.

In the design of the electrodes for a plasma gun, many significant details must be considered. It is to some extent the design of the electrodes which has given plasma spray coating technology its mystique and the reputation of being a "black art". Such, in fact, is not the case. Electrode designers work from a solid experience base and from first principles of materials and electrical engineering and plasma physics. There are complex features of the plasma spray process which are interconnected, making a test and evaluation matrix most complex. Considerable experience has been employed in the current design of the μ-gun for vacuum plasma spray applications.

Of special significance is the powder injector, as indicated in the schematic of Fig. 1. The powder is transported by a carrier gas (e.g., Ar, N_2) which, in general, is at ambient temperature. Thus, this gas, as well as the powder (arriving at a rate of the order of 2 to 10 kg/Hr.)

will distort the plasma flame through both flame disturbance and thermal quenching. Instabilities and turbulence, therefore, are introduced, these very importantly influencing the form and heat content of the flame. Particle melting efficiency and, thus, coating quality are thereby effected.

Power, heat transfer, cooling fluid flow, plasma and powder carrier gas flows are all important considerations in the design and operation of a plasma gun. Given below are such considerations as applied to the μ-gun.

III. THE NAVSEA VACUUM PLASMA SPRAY MICRO-GUN

The special features of the μ-gun involve simplicity and economics of construction and operation, the ability to process a large range of feedstock, and the ability for the gun to operate at high efficiency in a reduced pressure environment. Design, fabrication, and testing and evaluation of the μ-gun and the resultant coatings involved faculty, research staff and graduate research assistants of SUNY's Thermal Spray Laboratory. Design criteria were established for the NAVSEA Vacuum Plasma Spray Micro-Gun (VPSMG) from the academic and industrial experience of the Stony Brook group. The major design goals were grouped into three major areas:

1. Mechanical assembly
2. Operational spray parameters
3. Spraying, coating deposition and quality.

This grouping of design criteria enabled the design group members involved to contribute in individual areas without imposing preconceived limitations from the other two categories. When a design goal was proposed, conflicting criteria from the other two areas did not require immediate consideration. When all the input from the group members was assembled, the tradeoffs among the three groups and elimination of conflicting criteria were considered.

The end result of this process led to what were considered to be realistic, accomplishable design goals. Each of these major groups is listed separately, the criteria summarized and then described in detail where necessary.

A. Design Considerations

Mechanical assembly criteria were:

1. No critical O-ring seals
2. Minimum number of parts
3. Straightforward, foolproof assembly
4. Assembly and disassembly using screw driver, adjustable open-end wrench and pliers
5. Off-the-shelf material selection for gun components
6. Component fabrication by ordinary machine shop
7. Rugged gun and components able to be handled in the spray environment with no special treatment
8. Nozzle and cathode life definition by mechanical or electrical methods
9. Weight under 2Kg for the VPSMG
10. Integral powder ports

Only those goals that need further explanation are explained below.

No Critical O-Ring Seals

A critical O-ring is defined as any seal where the cooling water can leak into the plasma gas; Fig. 3. When water leaks into the plasma gas, the water can be carried into the arc chamber. When the water passes near or through the plasma arc it expands into steam and some of the steam disassociates into elemental components. As this expansion occurs back pressure builds in the nozzle bore and more heat must be absorbed by the cathode and anode. The cathode and anode are designed to absorb only approximately 37% of input power. When this is grossly exceeded, the nozzle melts and catastrophic failure occurs. Fig. 3 shows two critical O-rings. Present commercial guns have up to seven critical O-ring seals. Most seal failures occur due to dirt or misassembly. Elimination of these seals yields substantially greater reliability.

Minimum Number of Parts

The ideal situation is a rear gun body, insulator and front gun body with a total of three parts. This lowers inventory from the present dozen or more gun parts on commercial guns.

Weight Under 2Kg for Gun

This design goal would lessen the gun manipulator requirements, lowering capital costs. For an air spray version, the reduced weight would lessen operator fatigue when spraying in air.

Nozzle and Cathode Life Definition by Mechanical or Electrical Methods

For currently operating plasma guns, nozzle and cathode replacement is left to the discretion of the operator or is specified by process sheets as a function of "the number of parts sprayed". In the former case, operator judgement varies widely. Slight erosion may be cause for one operator to change electrodes, while gross spitting is justification for another. This can be a cause for varying coating quality. If nozzle change is a scheduled procedure, imperfectly operational-capable electrodes may be circulated out of use.

Component Fabrication by an Ordinary Machine Shop;

Off-The-Shelf Material Selection for Gun Components

This will allow the individual plasma installation to have parts fabricated at the lowest possible cost and not be dedicated to one or two suppliers. When a gun part shortage arises, parts can be fabricated locally

Rugged Gun and Components Able to be Handled in the Spray Environment With No Special Treatment;

Assembly and Disassembly Using Screwdriver, Adjustable Open-End Wrench and Pliers

Present commercial guns have special tools required for assembly/disassembly, nozzle change or cathode changes. These tools are usually obtainable only from the manufacturer and invariably are small. The obvious disadvantages are many.

Designing the gun and components for assembly by screwdriver, pliers and open-end wrench requires a ruggedness that compensates for the inaccuracy and force that can be expected by these tools. Present guns can be damaged by nicks on sealing surfaces of as little as 0.015 inch. This is another major source of premature gun failure. Designing components that can be dealt with in a shop environment enhances reliability and allows the operator to allocate more time to the coating operation.

Integral Powder Ports

Powder injection is critical to the success of the coating. If the powder is not injected into the flame in a controlled, repeatable way, coating quality will vary among spray events and in the worst case, within a single spray event. The three major ports of powder injection are the feed rate and gas flow, which are controlled by the powder feeder, and the injector, which is positioned at the nozzle; its location must be repeatable on most guns to within 0.020 inch. For some of the tungsten carbide coatings using 88% tungsten carbide in a cobalt matrix, even this tolerance is often found to be too wide. On the shop floor, normal practice is to only visually inspect powder port placement. This has given rise to errors, especially with operators having limited experience. Trading off powder port replacement (if the goal of no powder port clogging is met), it was our goal to eliminate placement errors.

B. Operational Considerations

Plasma spray parameters which were considered to be important are as follows:

- Ability to spray in vacuum or at atmospheric pressure
- Low power operation, below 30-35 kW
- Ability to accommodate most or all commercial power feeders
- Adaptability to existing commercial plasma gun controllers, both manual and automated
- Ability to utilize most or all commercial power supplies
- Reduced gas flow; below 80 SCFM (37.7 SLPM)
- Ability to "hard-start" with critical orifice controllers
- No damage from emergency stops
- Anode life in excess of 15 hours
- Cathode life in excess of 45 hours
- Ability to run at maximum power, 35 kW, with line pressures of 40 PSI
- Optimize gas injection to produce minimum vortex while achieving life objectives
- Investigate use of gas cooled cathode

Only those goals that need further explanation are expanded below.

Low Power Operation, Below 30-35 kW

Low power offers advantages, including: Lower capital costs for plasma gun support equipment, such as water cooling and power supplies. With lessened power requirements, the plasma system can be installed in many industrial areas without special high power requirements (e.g., aboard ship). This advantage yields the possibility of bringing the equipment to the site, thus decreasing turnaround time for the spraying operation.

Ability to Accommodate Most or All Commercial Powder Feeders

This is an important consideration in the placement of the powder port. Additionally, a recent trend in plasma equipment is to mix manufacturer's equipment in plasma installations. This is being seen in the latest equipment purchases of General Electric, Pratt & Whitney, Allison, Garrett and others.

Low Gas FLow; Below 80 SCFM (37.7 SLPM)

Low power operation allows the gas flows to be reduced without excessive nozzle erosion. The low gas flow reduces operating costs in gas consumption and in vacuum capital equipment, as well as in capital outlay for smaller vacuum pumps and filtering systems.

Ability to Hard-Start with Critical Orifice Controllers

Several older plasma controllers start the gun at full gas flow on both primary and secondary and at full amperage. This causes premature or catastrophic failure on many guns. While few of these orifice controllers are being manufactured, any gun able to withstand this type of startup will be immune to hand starts due to operator or machine error.

No Damage From Emergency Stops

During the gun's lifetime many energency stops (E-Stops) are expected. These type of stops are the immediate termination of power (voltage and amperage), primary and secondary gas, and water cooling. The transient high power, low gas, cooling shutdown can destroy nozzles in many guns. While an experienced operator can detect an E-Stop situation, many personnel will have less than three years experience. By designing-in an immunity to E-Stops, operator overhead is reduced and a more reliable system is produced.

Anode Life in Excess of 15 Hours; Cathode Life in Excess of 45 Hours

Many numbers are claimed for cathode and anode life. From our experience, these life durations are reasonable for a low-end cost nozzle, approximately

$100, and low-end cost cathode, $75 to $100.

Ability to Run at Maximum Power, 35 kW, With Line Pressure at 40 PSI

While most plasma guns operate at pressures of 90 PSI to 235 PSI, this exerts a significant stress on the hoses and attendant fittings. To reduce the cost of these $400-plus specialty components, lower pressure will enable shop-fabricated components to be substituted. Inventory reduction is an important by-product of this goal.

Optimize Gas Injection to Produce Minimum Vortex While Achieving Life Objectives

Higher vortices produce increased life by moving the arc root around the nozzle bore. The longer the arc root dwells at one spot, the more nozzle wear is produced. Higher plasma gas vortices are thus used. However, the greater the vortex, the more powder is spun-out of the plasma flame, lowering the DE and contributing to higher unmelted particle counts.

Investigate Use of Gas-Cooled Cathode

Gas cooling of the cathode has been successfully used in the welding industry and in some limited cases, plasma guns. Normal plasma guns such as the Plasmadyne and Metco Guns have a thermal efficiency of 63% of the input power into the plasma gas. Thirty-five percent of the input power is rejected through the anode and only 2% of the power is rejected through the cathode. Gas cooling of the cathode, although feasible, is limited by the objective of low gas flow.

Spraying, coating deposition and quality criteria which were considered include:

- Ability to spray a large range of coatings with minimum number of different nozzle types
- Ability to spray coatings of accepted industry quality
- Feed rates at operational power at least 50% of medium to high power commercial guns

- No powder port clogging while spraying
- Deposition efficiency within 80% of commercial guns

Only those goals that need further explanation are expanded on below:

Ability to Spray a Large Range of Coatings With a Minimum of Nozzles

Current commercial plasma guns have families of nozzles to spray different coatings. For some guns, such as the Metco 7M family, there are in excess of 12 currently available nozzles. This leads to large inventories and errors in choosing the proper nozzle for spraying. While no nozzle can currently spray all coatings, two or three nozzles should be sufficient to spray all commonly used coatings.

Ability to Spray Coatings at Accepted Industry Quality

The quality of coatings is determined by a combination of factors from among: hardness, unmelted particle count, oxide content, porosity, bond strength, tensile strength, bend-radii before cracking, as-sprayed surface roughness, finished surface roughness and thickness limitations for most coatings. The values for these "quality factors" are available from a large number of sources, including the powder suppliers themselves, academic sources, military specifications and gas turbine manufacturers. Minimum values are defined and the objective was established here to exceed minimum acceptable coating qualifications in all defined areas using commercially available powder.

Feed Rates at Operational Power at Least 50% of Medium to High Power Commercial Guns

Medium power was defined here as 30-35 kW to 55 kW and high power is 55 kW and up. A major advantage of arc plasma deposition is the high deposition rates that can be achieved in comparison to other methods such as PVD and CVD. If feed rates drop substantially from other plasma guns, the advantage enjoyed by arc plasma deposition would be lost.

Deposition Efficiency Within 80% of Commercial Guns

Deposition Efficiency is the amount of powder deposited on the substrate related to the powder feed rate. This is usually expressed as a percent number. If the DE falls substantially from presently accepted values, the economics used to establish the coating application may be destroyed. This is especially critical for high value materials such as tungsten carbide or many Ni-based alloys.

The detailed design and fabrication of the VPSMG is described in Section IV below.

IV. VPSMG - DESIGN AND CONSTRUCTION

A. Overview

The design and construction of the VPSMG involved empiricism and was based on considerable experience with plasma guns. In Fig. 4 are shown the six plasma gas injection approaches which were evaluated for the small gun. After considerable study of various guns' I-V characteristics, a vortex design was chosen. The I-V characteristics of this final nozzle design are shown for various argon plasma gas flows in Fig. 5, where a stable plasma is obtained for flows between 30 and 60 SCFM.

The details of the gun parts are given in Figs. 6a-d, where 6a is the anode, with the water cooling tubes brazed on; 6b is the delrin insulator cap (the plasma gas entry port is seen on the internal diameter); 6c is the cap with the tungsten cathode in place; 6d is the fabricated gun. Fig. 7 is a photograph of a completed gun.

The engineering drawings for the VPSMG are given in Fig. 8. It is to be noted that these parts are simple to have machined in an ordinary machine shop and, again, can be put together in only one way, making this a very practical gun for Navy operational needs. For operation in air, Fig. 9a, b and c shows the plasma flame of the VPSMG at three different power levels, 5, 15 and 25 kW, respectively.

The gun-chamber arrangement is shown in Fig. 10, with details of the originally proposed chamber given in Fig. 11. Subsequent considerations led to a redesign, with the gun-handling electric motor being mounted at the top of the chamber, as shown in Fig. 12, which is the final design of the water cooled chamber. In the current configuration (Fig. 12), there are three ports, the ones at the ends being available for the emplacement of rotatable specimen-to-be-coated shafts. The vacuum line feedthrough can easily be located on the chamber wall. Note that for current operation, the vacuum is maintained by a relatively low capacity mechanical pump, and filtration is achieved by loading the vacuum hose with glass wool. This arrangement permits operation of the VPSMG for reasonable periods of time without apparent damage to the pump.

The VPSMG flame is pictured in Fig. 13 while operating at 100 torr. The length of the flame is approximately 6 inches. Under extended periods of operation (e.g., 30 minutes) no apparent deterioration of any of the system's parts was observed.

B. Detailed Design Considerations and Test Matrix

Meeting the design criteria within budget and the frame of this contract required an evolutionary plasma gun design. The starting nozzle design was a flare starting at the cathode, leading to a straight bore. This was based on experience spraying large families of coatings with Metco, Plasmadyne, Bay States, Avco, and Plasma-Technik plasma guns. The starting bores were 0.250 inch and 3/16 inch, angles of 15° and 30° and flare openings of 0.438 inch and 0.539 inch. An integral, external powder port was chosen to minimize clogging. The powder port was designed to be fabricated separately and brazed into place to reduce nozzle fabrication costs and to allow for nearly immediate spray feasibility tests. Spraying early in the testing may seem premature; however, excessive vortex or low heat flux can be immediately noted by a rapid, non-optimized spray test. A generic test nozzle typical of those used in the test program is shown in Fig. 8a.

Most cathodes in current guns eventually erode to a flat or concave tip, therefore, the starting cathode design included a flat tip. Further, most plasma gun cathodes include a large body, greater than 0.250 inch, tapering or rounding at the end. This is useful at high power to prevent melting of the cathode. In the VPSMG, the ultimate power does not require a large cathode, and to meet other design criteria, straight, small diameter, 1/8 and 3/16 inch welding cathodes were chosen for testing (Fig. 6c).

Gas injection posed the most vexing problems. There are two extremes to introducing the plasma gas into the chamber; vortex, where the gas spins inside the chamber and nozzle bore; and radial gas flowing straight through the chamber and bore. The two injection schemes can be seen in Fig. 4. The immediate advantage of radial flow is the powder injected into the plasma flame is carried forward with little or no radial components. By simple changes in powder injector bore diameter and carrier gas velocity, the powder particles can be inserted into any area in the plasma flame. The penalty for this is drastically reduced nozzle life since the arc root can dwell on a spot within the nozzle ID.

Vortex flow moves the arc around the nozzle bore, reducing erosion and greatly increasing nozzle life. Powder injection into a spiraling plasma flame has a special set of challenges due to the nature of the powder. Each powder particle size is accelerated to maximum velocity at a different rate. The lightest particles reach terminal velocity the earliest and are spiraled out of the flame and can resolidify before reaching the substrate. If the particles in the middle of the particle distribution melt and reach the substrate, usually the largest and heaviest particles only partially melt before arriving at the substrate. This situation is not a serious problem if the power is increased; the consequence though is poor melting efficiency. For commercial guns with high vortex, dividing the power to melt a quantity of powder at published feed-rate by the published power level needed to spray the material yields a melting efficiency in the low single digits. The approach of high vortex, high power is normally employed by most plasma guns. Our approach for the VPSMG tests was to compromise between vortex and radial flow. This is accomplished by placing the injection holes less than the tangential distance D_T as shown in Fig. 8f. Similarly, partial vortex flow can be generated for rear gas injection techniques.

Cooling schemes for the nozzle and cathode were reserved until the final internal configuration was determined. For the tests, maximum, reasonable amounts of cooling were used for both cathode and anode in the form of high volume, greater than 4 GPM, and 90 PSI water.

A test sequence was developed to obtain the gun geometry that started with the most dependent design variable to the least effective design change. There is little information available on this procedure. The relative importance of changes and the chosen test geometries were based on the experience of the design team members. While the absolute optimum gun design may not have been found, using this method provided a workable design in a realistic amount of time and effort.

The starting geometry and test matrix appear in Table I and Fig. 5. Gas chamber size was 0.700 bore and 0.300 inch thick and was fixed throughout the tests.

Proven, off-the-shelf materials were chosen for the construction of the gun. Oxygen free, high conductivity (OFHC) copper for the nozzle, Delrin or nylon for the insulator and thoriated tungsten for the cathode. The test matrix appears in Table I.

C. Testing

The test matrix was executed using argon primary at 100 PSI and secondary at 50 PSI. These are commonly used gas pressures. The configurations were executed by testing at set primary and secondary gas flows at 100, 200, 300 and 400 ampere settings. The resultant voltages were recorded and the data graphed. A sample graph of taper angle and flare opening is shown in Fig. 5 labeled "rear vs length of tests". Spitting, instability, "tearing", plasma not filling the bore and other observations were recorded. Obvious bad tests were immediately terminated. Power supplied to the gun had two paths of rejection, the gas and the cooling water. Thermal efficiencies were found by measuring the temperature of the water inlet and outlet, water flow and subtracting the power in the water from the total supplied power.

The number of configurations that needed to be tested dictated inexpensive, quickly fabricated components. The water jacket parts for the OFHC copper nozzle were brazed plumbing fittings as was the water jacket for the cathode: Figs. 8b and g. This was so successful in testing that it was incorporated in the final design. Little choice was available in the construction of the insulator due to the need for an engineering plastic to withstand the UV radiation from the arc and retain dimensional stability at operating temperature. The two leading candidates were acetal or polyamide-imide. Both of these materials are proven in plasma gun construction. The latter material, polyamideimide enjoys a slight advantage in this particular design due to its higher temperature capabilities. However, this advantage is more than offset by the lead times to obtain the material and the unit cost of the fabricated part. Polyamideimide is a Dupont product and is marketed under the Vespel trade name.

Acetal is available from several manufacturers and is used for the insulator. Delrin, a homopolymer acetal from Dupont was employed. Other materials have been utilized in the past but have some major defects. A brief list of those materials and their attendant problems are:

Nylon	-	Machining leaves burrs that are difficult to remove. Nylon will absorb water and swell thereby changing dimensions.
Plexiglass	-	Inconsistent UV resistance, leading to cracking; may have poor impact resistance due to machining methods.
Ceramics	-	Poor impact resistance; needs special handling on assembly.
Styrene, ABS, etc.	-	Low temperature plastics not suitable for this application.
Laminates	-	Difficulty in obtaining consistent surface finish from multiple machining sources.

For the first tests, cathode size showed similar I-V characteristics with little degradation of the tip on either the 1/3 inch or 3/16 inch diameter. This was 2% thoriated tungsten welding rod used in TIG welding. Since 1/8 and 3/16 inch diameters gave similar results, the more common 1/8 inch diameter rod was chosen.

For the second tests, bore size was changed to a 15° and 0.438 inch flare opening. Tearing, the inability of the plasma to fill the bore, was present at power levels below 12 to 14 kW with the 3/16 inch bore. The tearing was observed as the plasma flame coming out of one side of the bore, a tearing sound and the plasma flame suddenly flipping to the other side of the bore. Feeding into this moving plasma flame is impractical. At higher powers, 40 to 42 kW, the 3/16 inch bore showed no spitting and little wear. For this low power gun, the 0.250 inch bore was chosen.

The third tests were flame opening and taper angle. The 30° angle at both the 0.439 and 0.539 inch flare openings showed wear and blackening at the angle break at flows below 60 SLFM (28.3 SLM). Operation with 0.539 and 0.439 inch flare opening and taper angle of 15° showed similar results for the nozzle. The insulator, however, showed some heat effect with the 0.539 inch flare. Both the 0.539 and 0.439 inch flare nozzles were then run at 30 kW for 1 hour. The initial observation of insulator over-heating with the 0.539 inch flare was confirmed. A nozzle with 0.438 inch flare and 15° taper angle was retained for further testing.

The fourth tests, amount of vortex flow, produced unexpected results. Pure vortex with four holes injecting perpendicular to the axis of the gun was used up to this time. See Fig. 4. Radial flow with four holes produced the expected spitting at above 20 kW. The one-half vortex flow was tested and the next iteration, 0.350 inch from center line, produced the best results to that point. A quick spray test with NiCr powder showed promising results. An inexpensive, easy to assemble, four hole gas injector and insulator was proving to be a very difficult design problem. In an effort to reduce the number of gas injection holes, the test matrix was expanded to include testing the number of gas injection holes versus gun performance. The base line test was made with one gas injection hole with a cross-section area equal to four of the existing holes. To the suprise of all the team members, the performance of the gun at all power levels was nearly identical to the four holes. Only some minor increase in nozzle wear at above 25 kW was noted. The established results in commercial guns show that nozzle wear is dramatically decreased with multiple gas injection holes. This is because gas starved areas opposite the injection site have reduced gas velocity, allowing the arc root to dwell at that particular area.

At lower power this proved not to be the case. In an effort to find the power level where multiple holes become required, the gun was assembled with a single gas injection hole insulator, 3/16 inch nozzle, increased water flow and pressure and tested at power levels from 25 kW to 40 kW. These tests showed no wear to 29-30 kW and localized wear at above 32-33 kW. The nozzle was rotated 90° and a second wear spot occurred 90° from the first spot at the elevated power. This finding is significant in reducing the part cost for the μ-gun. Similar results for single and multi-hole insulators should be found for other commercial guns. This is supported by work done at SUNY at Stony Brook showing increased nozzle life in Metco 3M plasma guns with multiple hole injectors.

The fifth tests were varying the cathode-anode gap. The starting gap was 0.0625 inch and was increased to 0.090 inch. There was a voltage increase with increasing gap up to 4 volts with the 0.090 inch gap. Slight secondary gas changes of approximately 1 SLFM (0.472 SLM) did correct the voltage differences. This secondary gas change is not expected to effect the coating, which leaves a fairly wide part tolerance. Since the cathode-anode alignment can be determined by the flatness of the mating parts, further testing was conducted to determine the minimum gap due to part tolerance stackup. A test was conducted by shimmying the insulator to cock the cathode, leaving a gap of 0.032 inch on one side of the cathode and 0.093 inch on the other. No real changes were noted and there was no increased nozzle wear. However, there was a slight increase in frosting on one side of the cathode, which was expected.

The final internal configuration for the gun was:

0.250 inch bore, 1.050 inch length

15° angle

0.438 inch flare opening

0.700 inch insulator bore with one injection hole 3/32 inch diameter

0.250 inch from center

0.060 inch gap

1/8 inch diameter thoriated tungsten cathode.

The thermal efficiency of the gun was tested by recording the inlet and outlet temperatures and the water flow. The gun power has only two places to escape, the water and the plasma gas. By subtracting the power rejected from the inlet power, the thermal efficiency of the gun was found to be 66% to 69% efficient in power going into the gas. This compares very favorably with commercial guns, which usually have 60% to 63% efficiency.

Several powder injector diameters were tested, the 0.090 inch bore giving the most consistent feeding characteristics over a range of metals and ceramics. The 0.060 inch bore projected the tungsten carbide through the plasma flame, and the 0.120 inch bore allowed some of the ceramics, such as alumna, to bounce-off the bottom of the plasma flame.

All the team members have in the past had some problem with removable powder ports. The majority of these problems stemmed from misassembly, wrong choice, or alignment problems by inexperienced operators. Since one criterion for the μ-gun is foolproof assembly, the powder port was tested as an integral part of the nozzle. Preliminary spray tests showed good sprayability with a wide range of materials. The first attempt at spraying several materials showed good results. The parameters shown in the Table below are the first tests of the final gun configuration and in no way should be understood to be optimized: The parameters are a starting point at 1 atmosphere for further development.

Material	Argon Flow SLFM (SLM)	H_2Flow SLFM (SLM)	Amps	Volts	Power kW	Carrier Flow SLFM (SLM)	Feed Rate lb/hr
NiCr	80 (37.8)	8 (3.8)	400	55	22	5 (2.3)	7
Al_2O_3	40 (18.9)	6 (2.8)	500	55	27.5	5 (2.3)	4
Aluminum Bronze	80 (42.5)	2 (0.9)	400	45	18	5 (2.3)	5
Alumna-Titania	65 (30.7)	8 (4.3)	450	55	22	5 (2.3)	5

The spray distance for these tests were 2 1/2 to 3 inches. The traverse speed was approximately 10 ft/min. The Deposition Efficiency (DE) and hardness for these materials were:

Material	DE	Hardness
NiCr	65	R_B 88
Al_2O_3	65	R_C 55
Aluminum Bronze	75	R_B 77
Alumna-Titania	65	R_C 55

Comprehensive coating evaluation was not undertaken with these preliminary spray parameters. The above results are within 80% of commercial gun claims and in some cases, such as the aluminum bronze, exceed published results. A tungsten carbide was also sprayed and those results are compared with a commercial gun, the 7MB, spraying the same material. Tungsten carbide coatings comprise a large family and the choice was made to test one of the more common cobalt tungsten carbides; 17% colbalt, tungsten carbide balance, size of -53, + 10 microns.

In Figure 14a-d are shown cross-sectional micrographs of three VPSMG-formed coatings of Triballoy-400, NiCr and Ni. These are representatives of many spray tests which were carried out. The results of the preliminary test program we believe are very encouraging.

V. CONCLUSION

The design of a simple modular plasma spray gun has been developed and fabricated for use in either a reduced pressure or ambient environment. The economy and simplicity of this gun, as well as ease and low cost of operation, offer a number of novel application engineering opportunities.

TABLE I

TEST MATRIX

Starting Configuration

0.250" Bore

15° Angle

0.438" Flare Opening

Maximum Vortex

0.060" Gap

First Tests - Cathode Size Flat Tip

1/8 inch

3/16 inch

Second Tests - Bore Size

0.250 inch

3/16 inch

Third Tests - Flare Opening and Taper Angle

Flare Opening	Taper Angle
0.438	15°
0.438	30°
0.539	15°
0.539	30°

Fourth Tests - Amount of Vortex Flow Using Four Holes

Radial Flow

Maximum Vortex

1/2 Maximum Vortex

Next test dependent on results

Fifth Tests - Cathode Anode Gap

- Start at 0.0625 inches
- Vary as indicated by results

Figure Captions

Figure 1. Electrode-powder injector configuration in standard plasma gun. Important adjustable powder injector parameters include: C and B as well as the angle of injection. The nozzle diameter, A, will be important in determining the values of B and C.

Figure 2. Centerline plasma temperature versus spray distance at different ambient pressure levels. After "Protective Coatings and Their Processing - Thermal Spraying"; Plasma-Technik, 1984.

Figure 3. Critical O-ring seal locations for standard plasma spray gun.

Figure 4. Plasma gas injection designs.

Figure 5. Current-voltage characteristics for the VPSMG for various plasma gas (argon) flow rates.

Figure 6. Construction stages of VPSMG.

a. Nozzle with water cooling tubes brazed-on.

b. Delrin insulator with plasma gas injection port.

c. Insulator with cathode assembly installed.

d. Completed VPSMG.

Figure 7. Completed VPSMG with tubing in place.

Figure 8. Drawings of machined parts for VPSMG.

a. Nozzle of OFHC copper.

b. Nozzle braze details of cooling system.

c. End ring.

d. Spacer.

e. Plate of Delrin.

f. Insulator of Delrin.

g. Cathode brazing detail.

h. Cathode body.

Figure 9. VPSMG plasma flame in ambient pressure environment (air):

a. 5 kW

b. 15 kW

c. 25 kW

Figure 10. Schematic view of entire VPSMG System.

Figure 11. Original exploded view of vacuum tank and gun handling.

Figure 12. Final VPSMG System assembly. Note that both end hatches are triply hinged to facilitate alignment.

Figure 13. VPSMG operating at 30 kW under a chamber pressure of 100 torr.

Figure 14. Micrographs of VPSMG-formed coatings. (Coating at top).

a. Tribaloy-400; 100X

b. NiCr; 200X

c. Ni; 200X

d. Ni; 400X

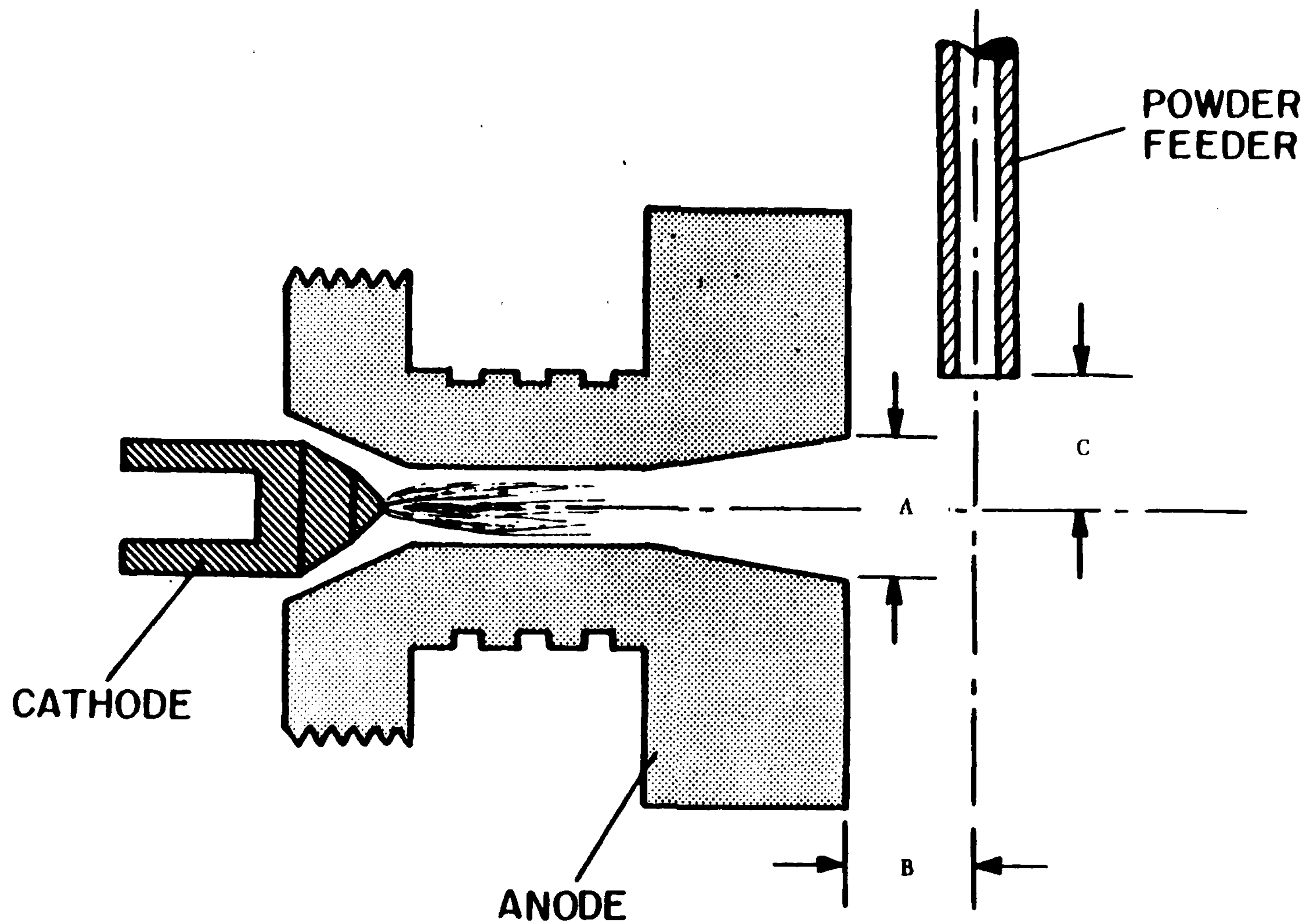
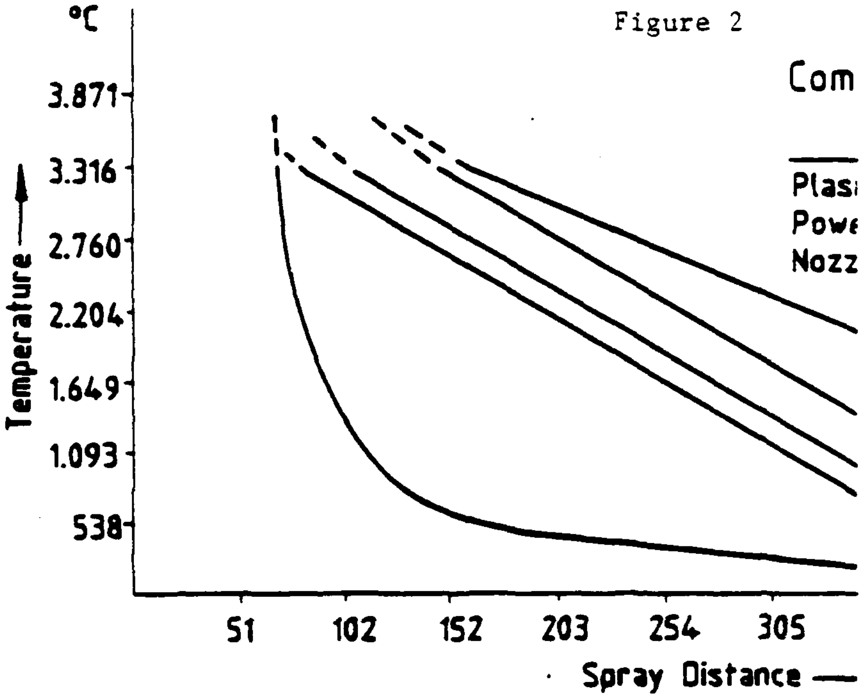
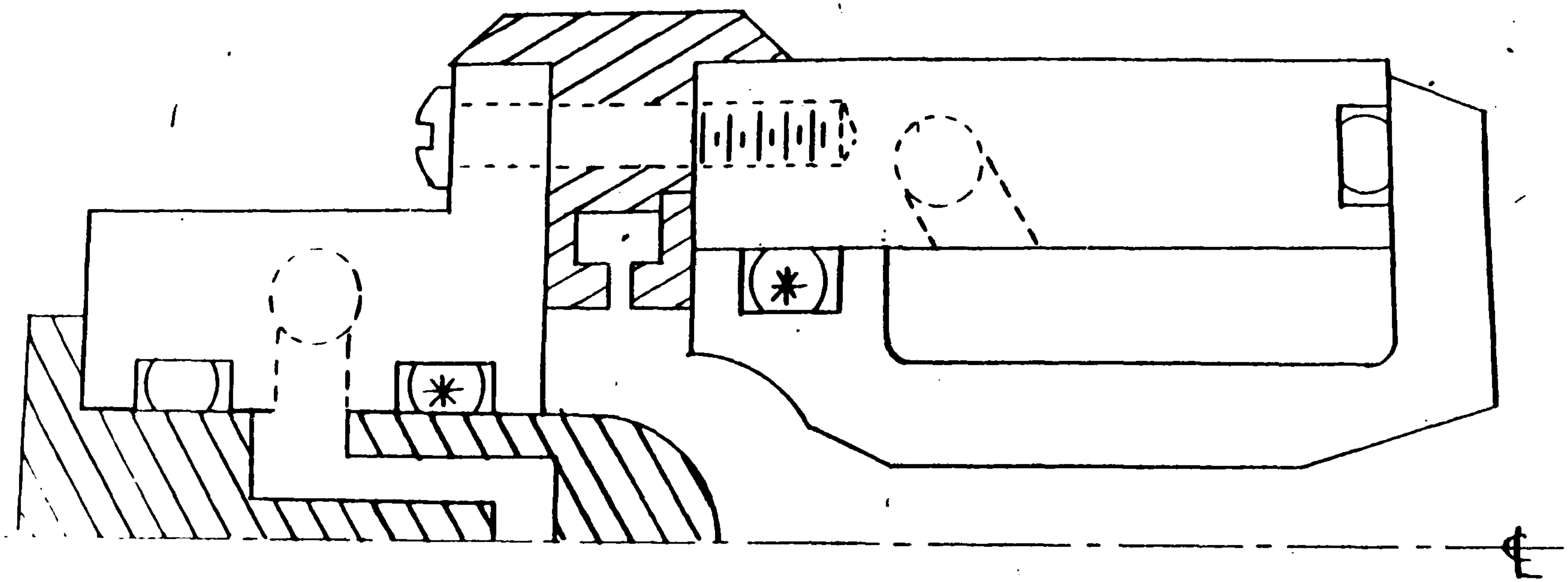


Figure 1

Figure 2


°C
3.871
3.316
2.760
2.204
1.649
1.093
538
Temperature
51
102
152
203
254
305
Spray Distance



* - CRITICAL O-RING SEAL

Figure 3

PLASMA GAS INJECTION DESIGN

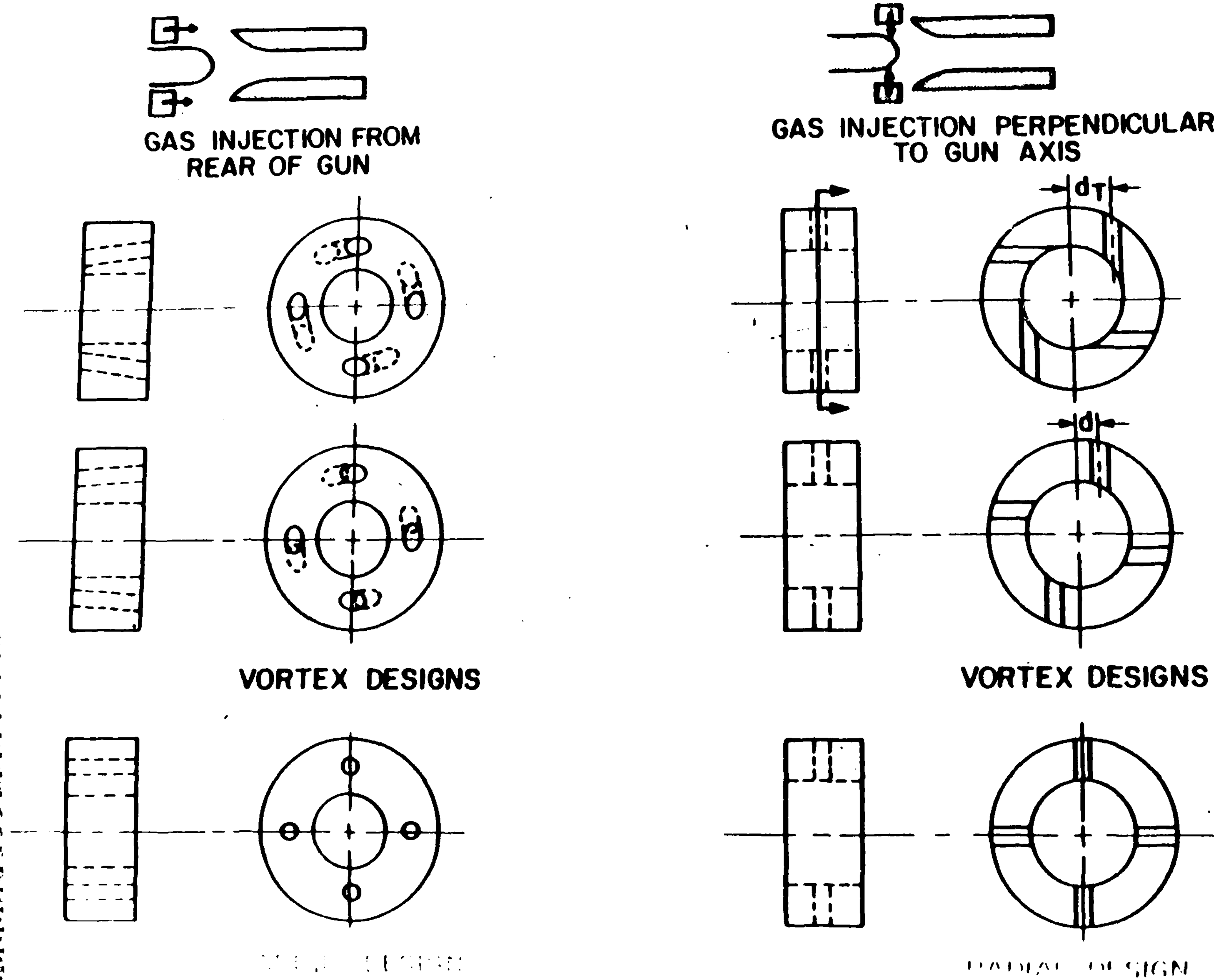
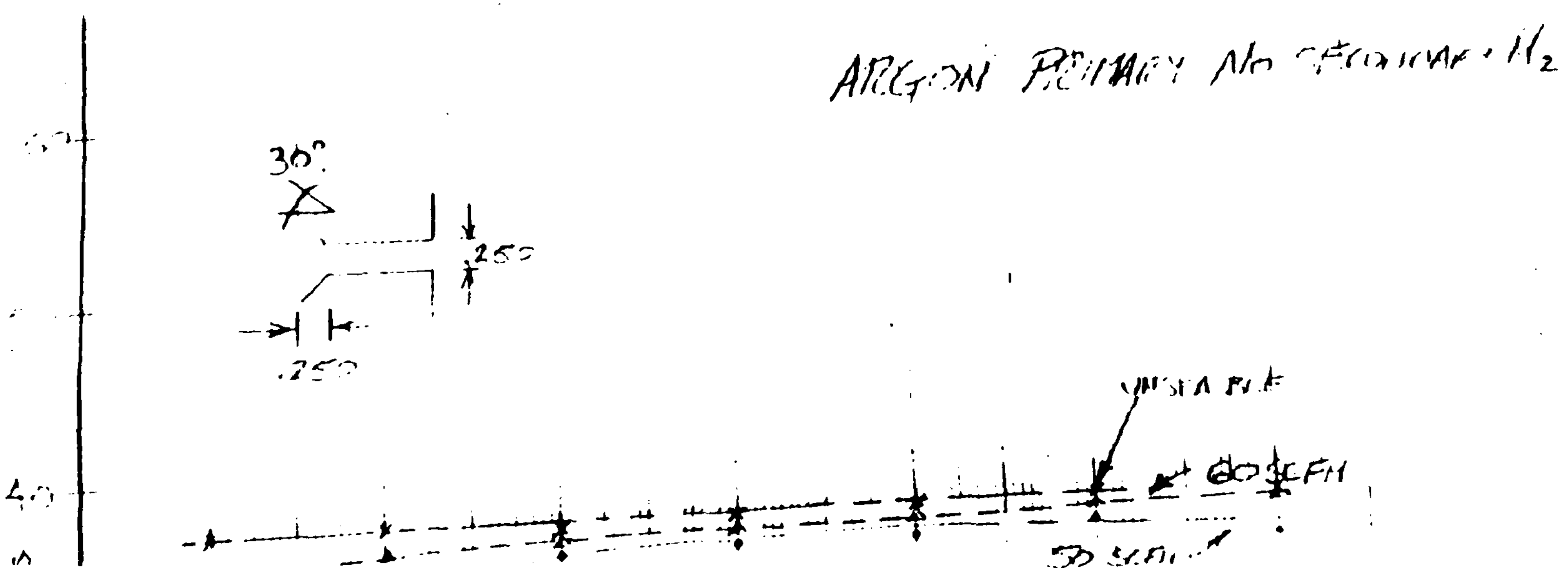


Figure 4

PEAP Δ VS LENGTH OF Δ TESTS



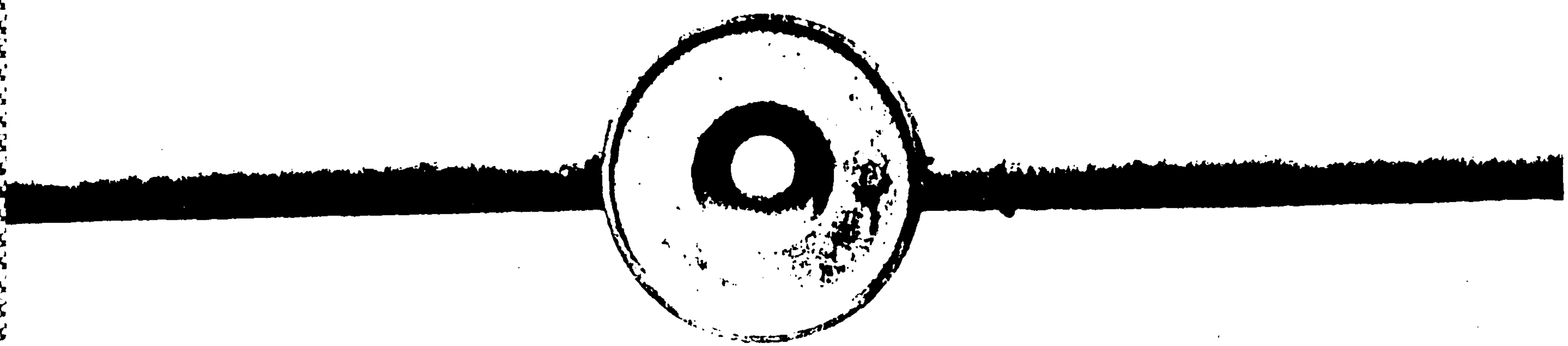


Figure 6a

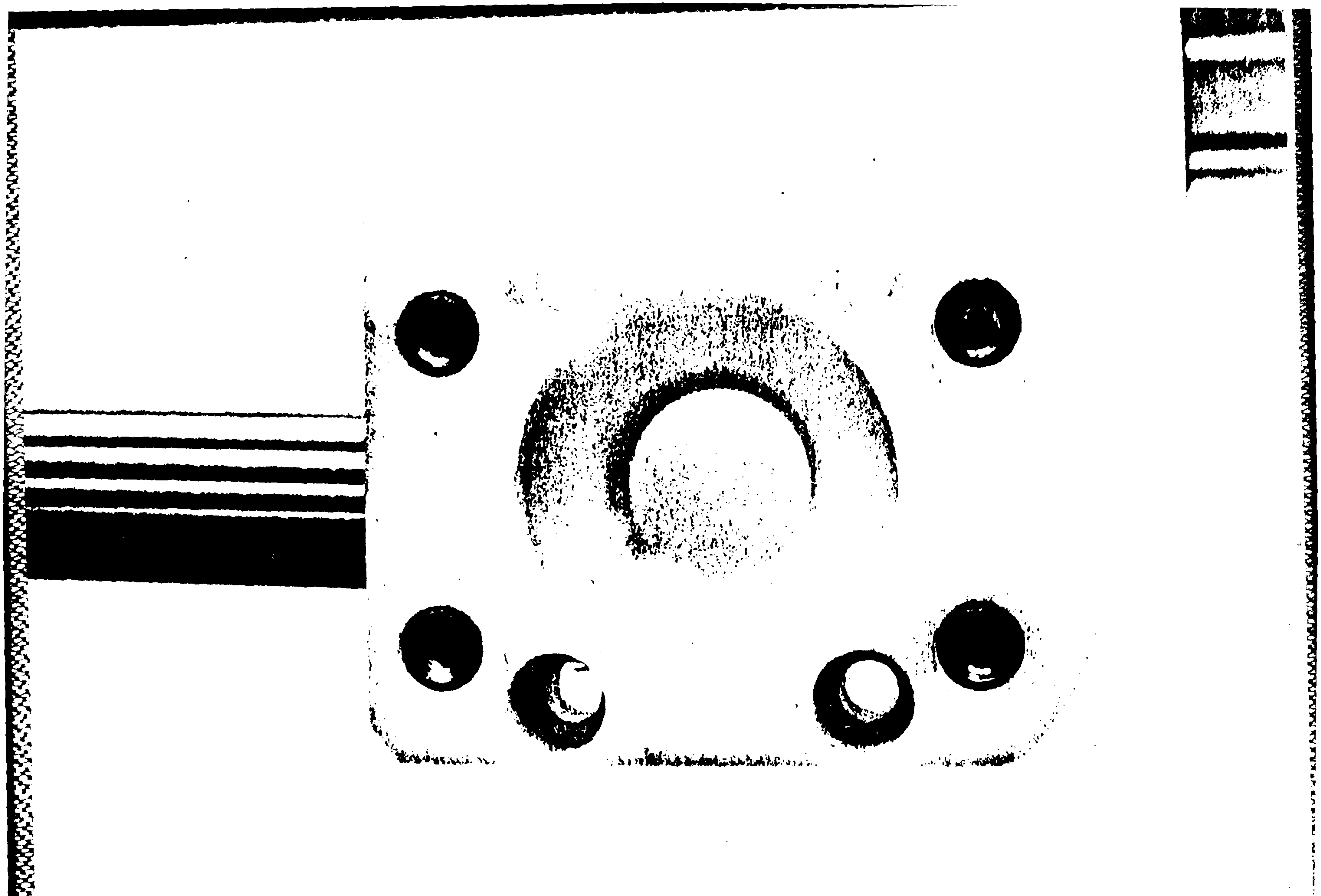


Figure 6b

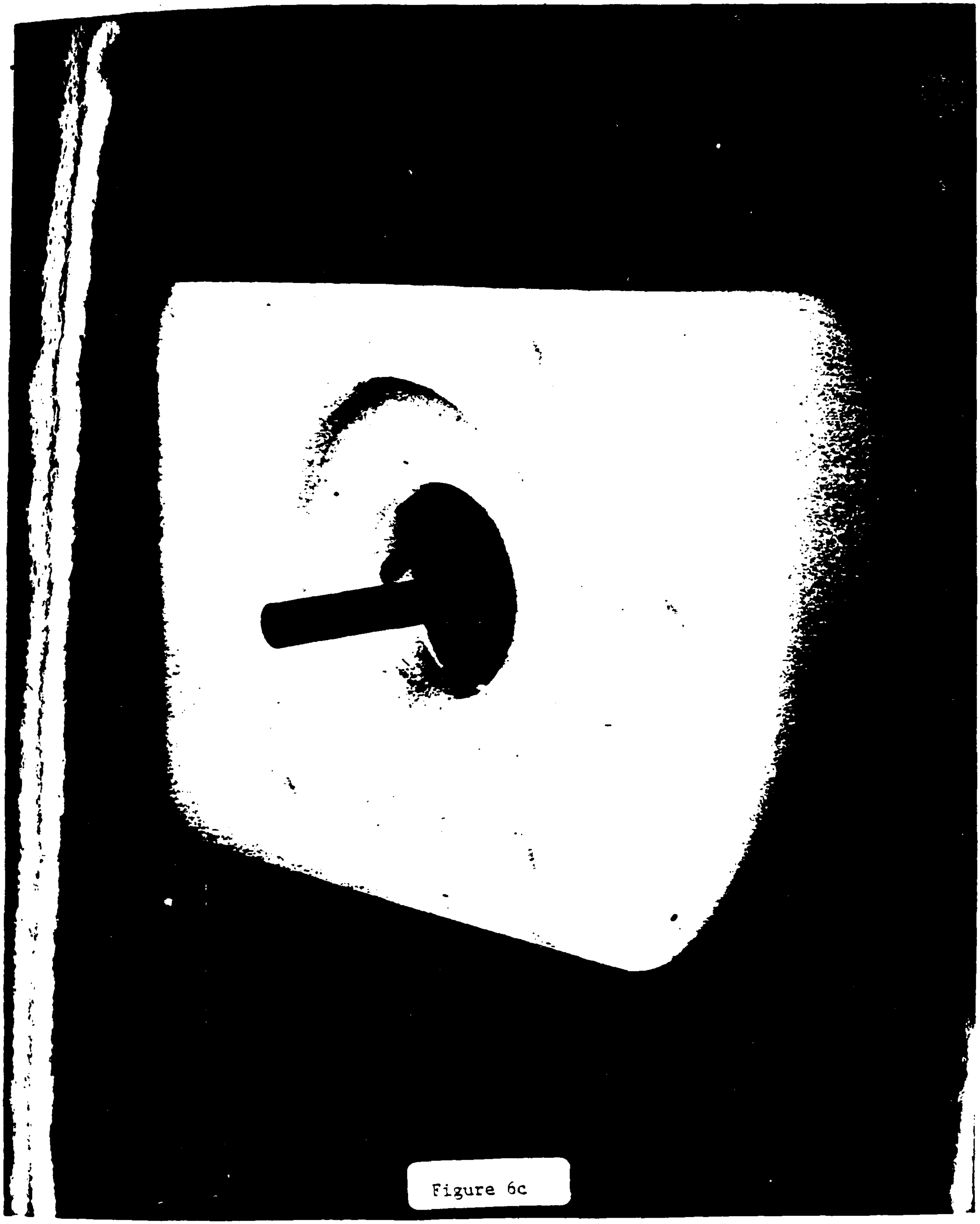


Figure 6c

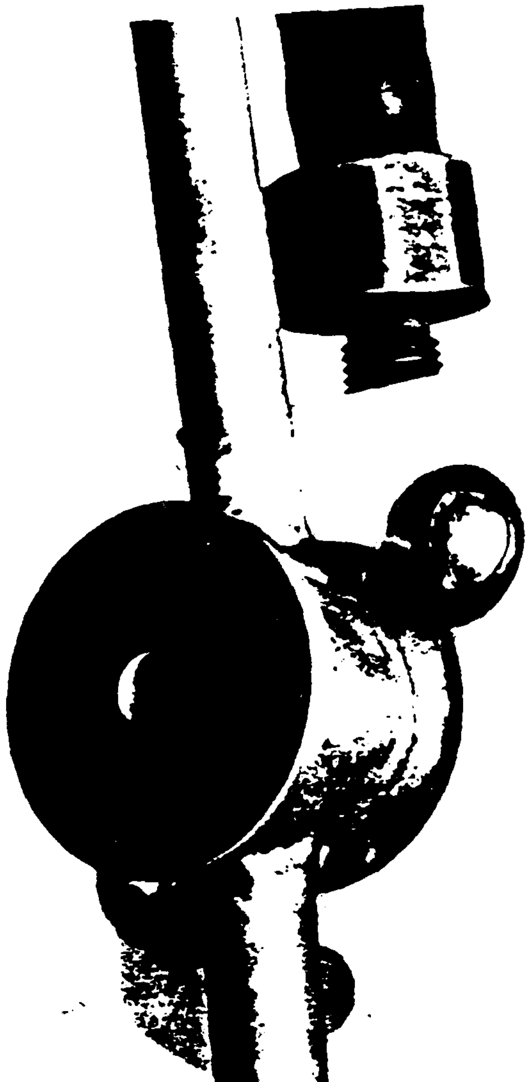


Figure 6d

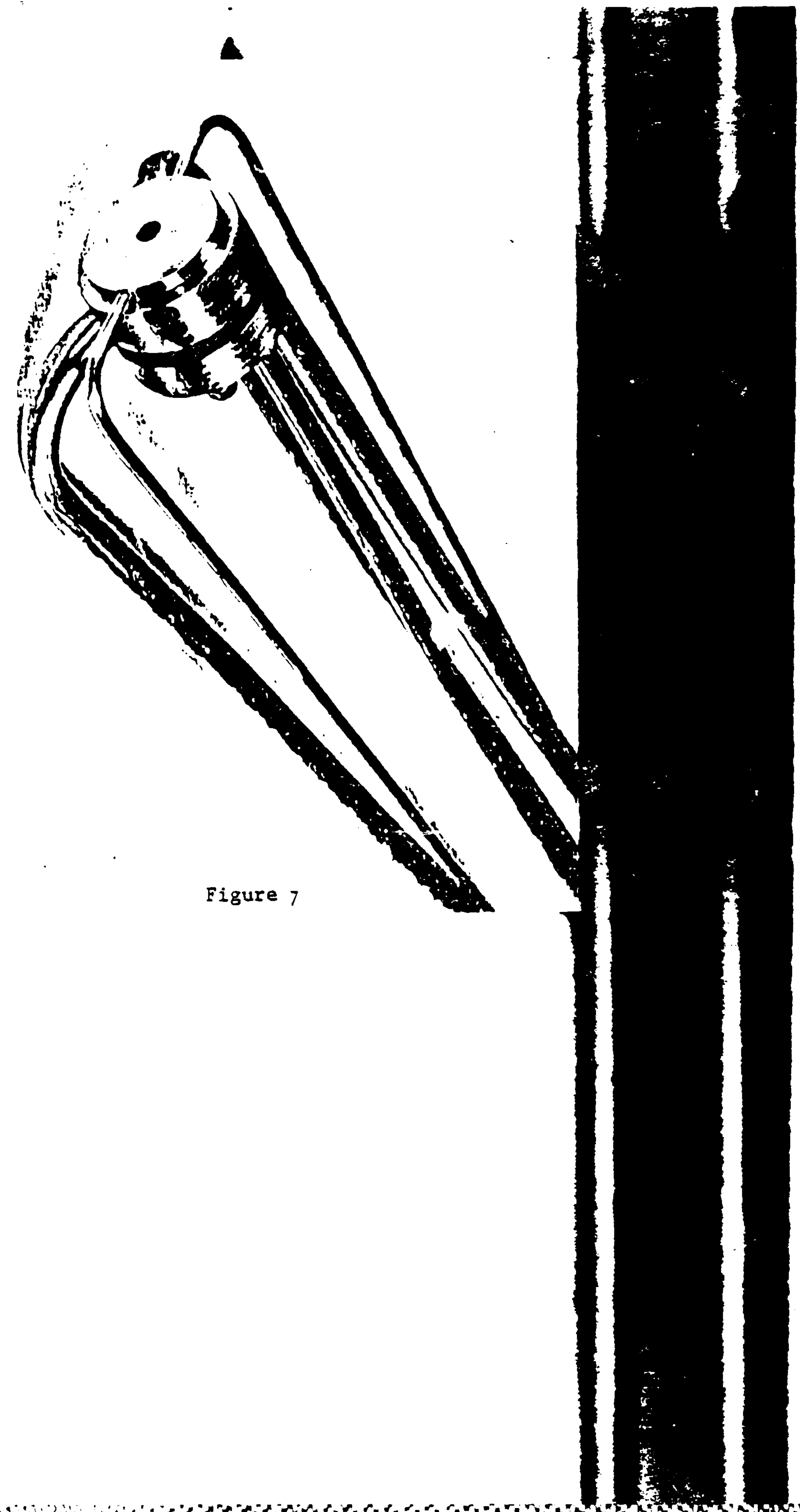
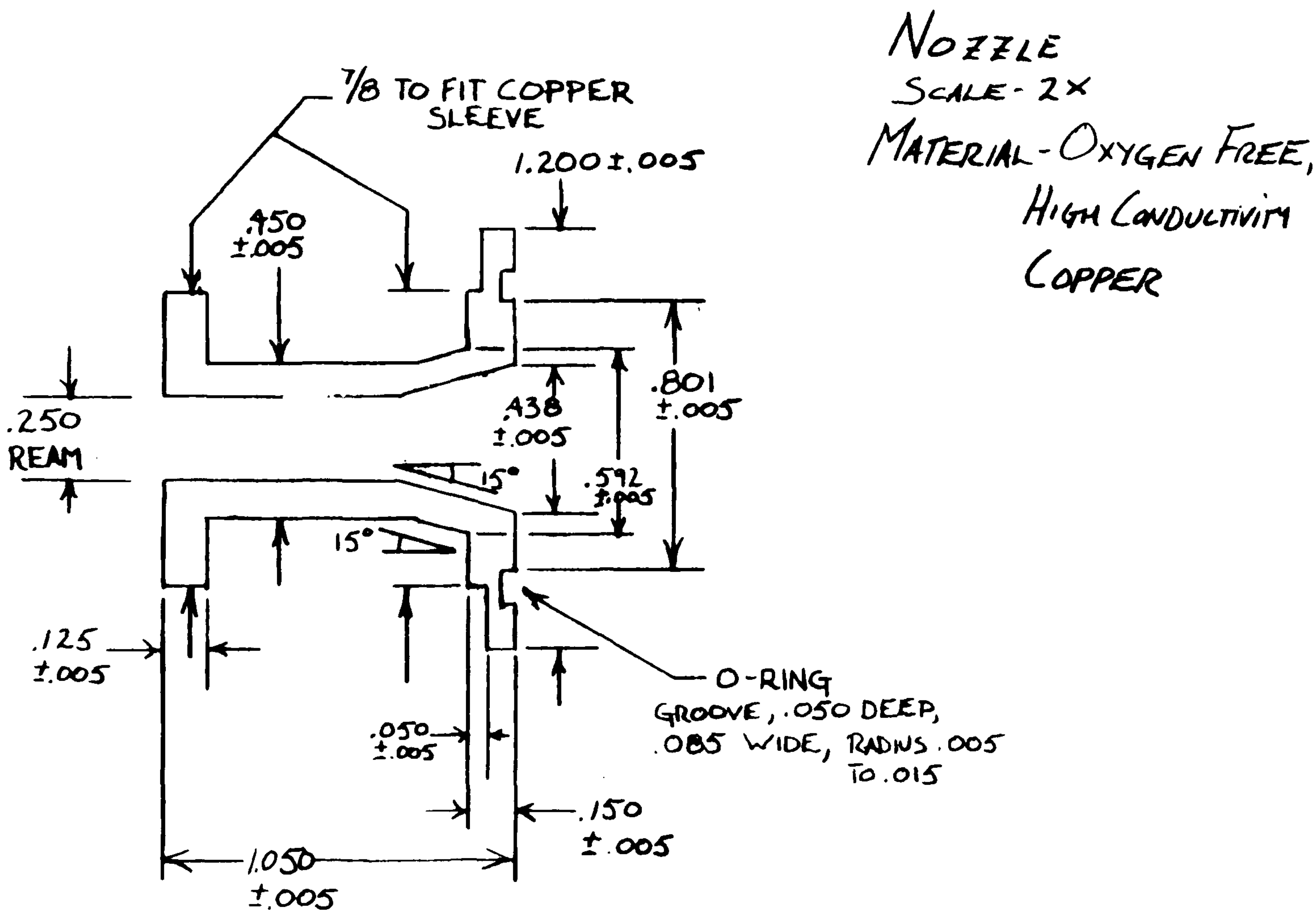
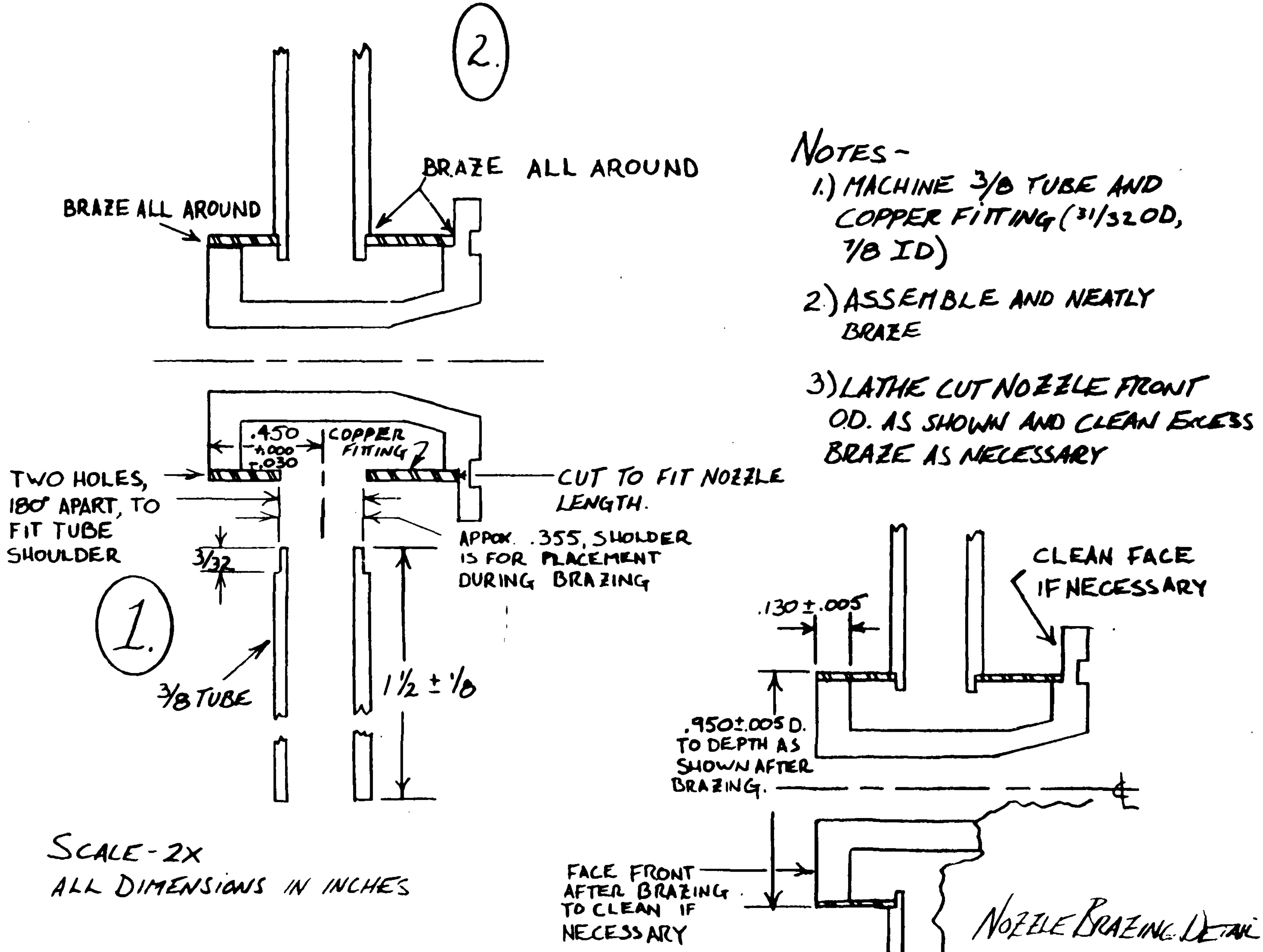


Figure 7



Nozzle

Figure 8a



Nozzle Cooling Seal

Figure 8b

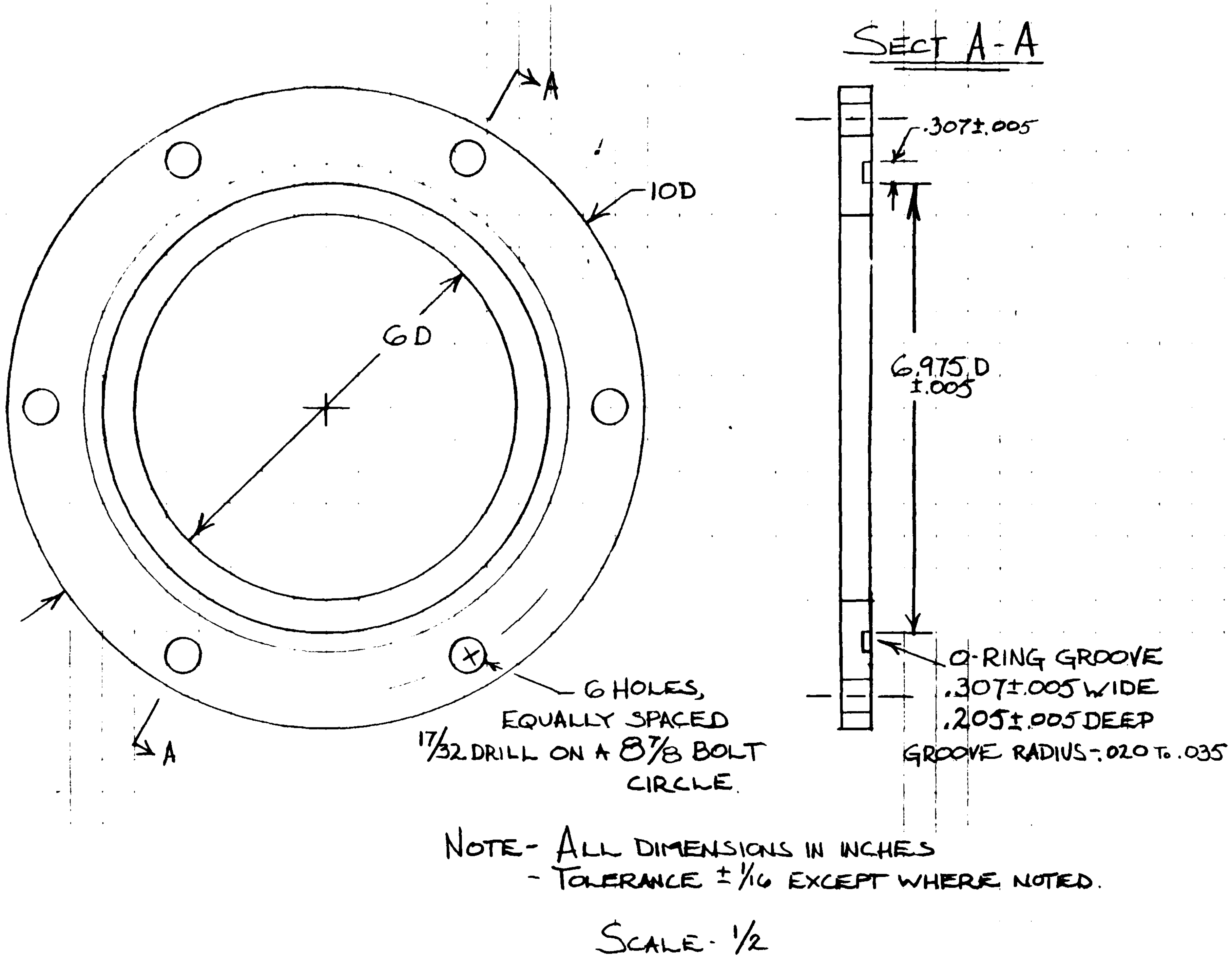
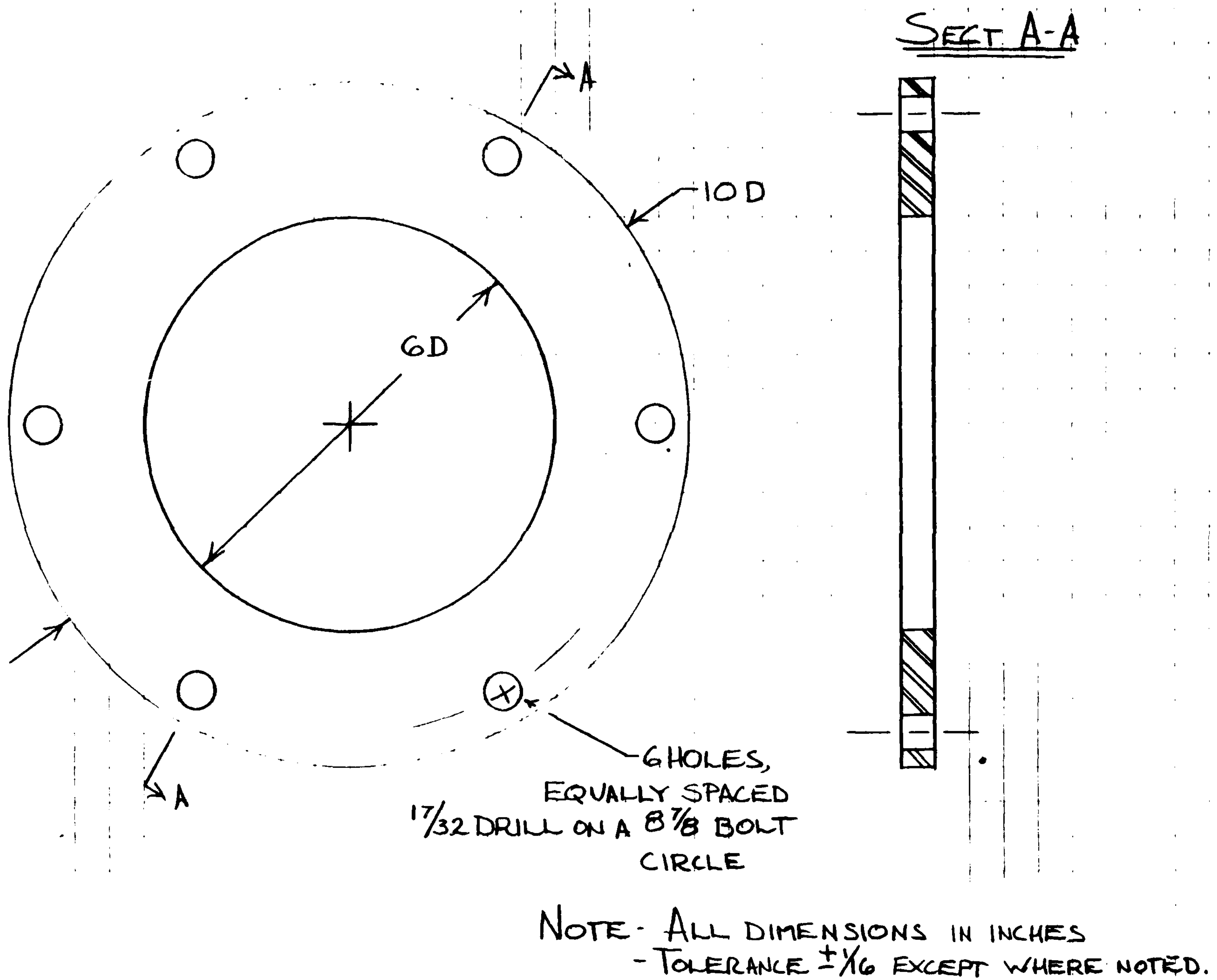
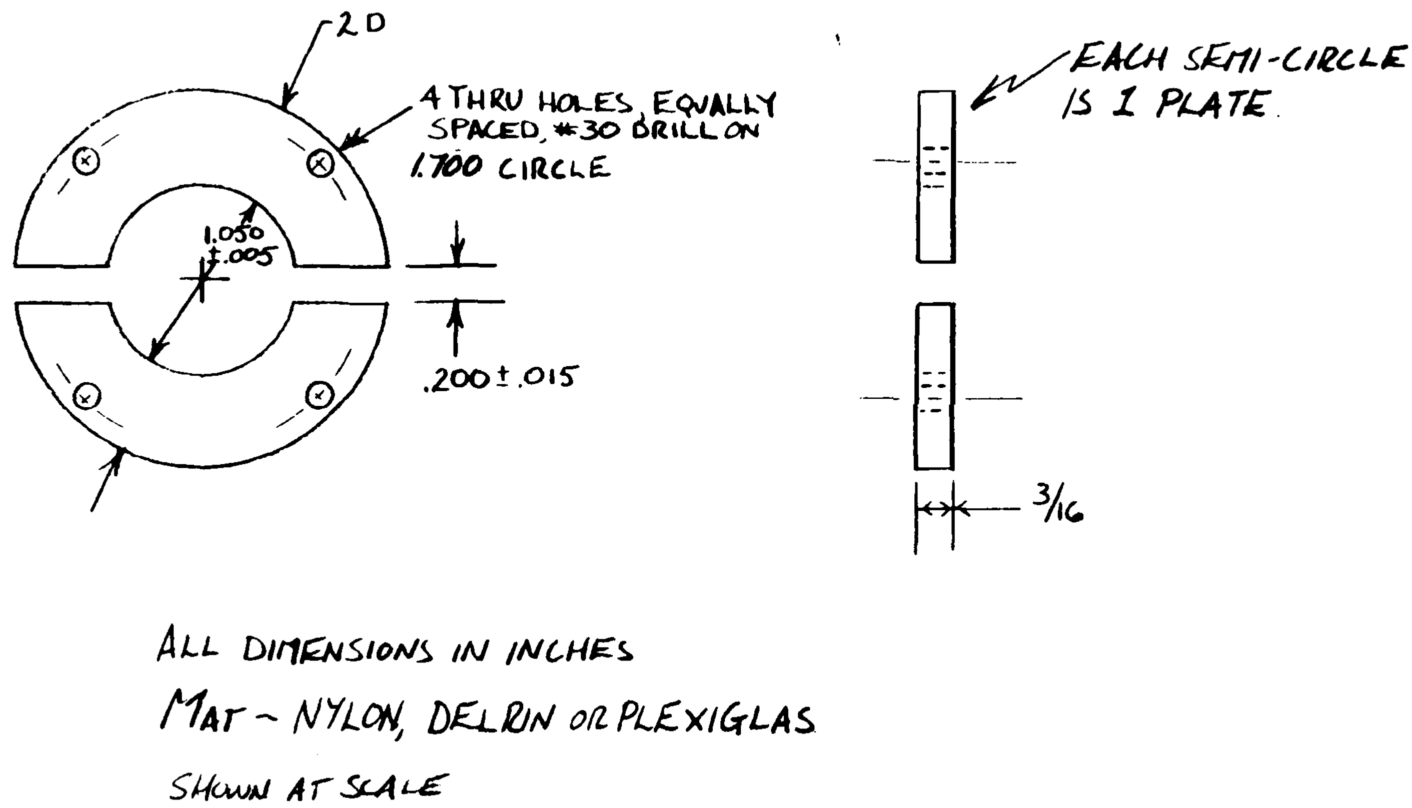


Figure 8c - End Ring



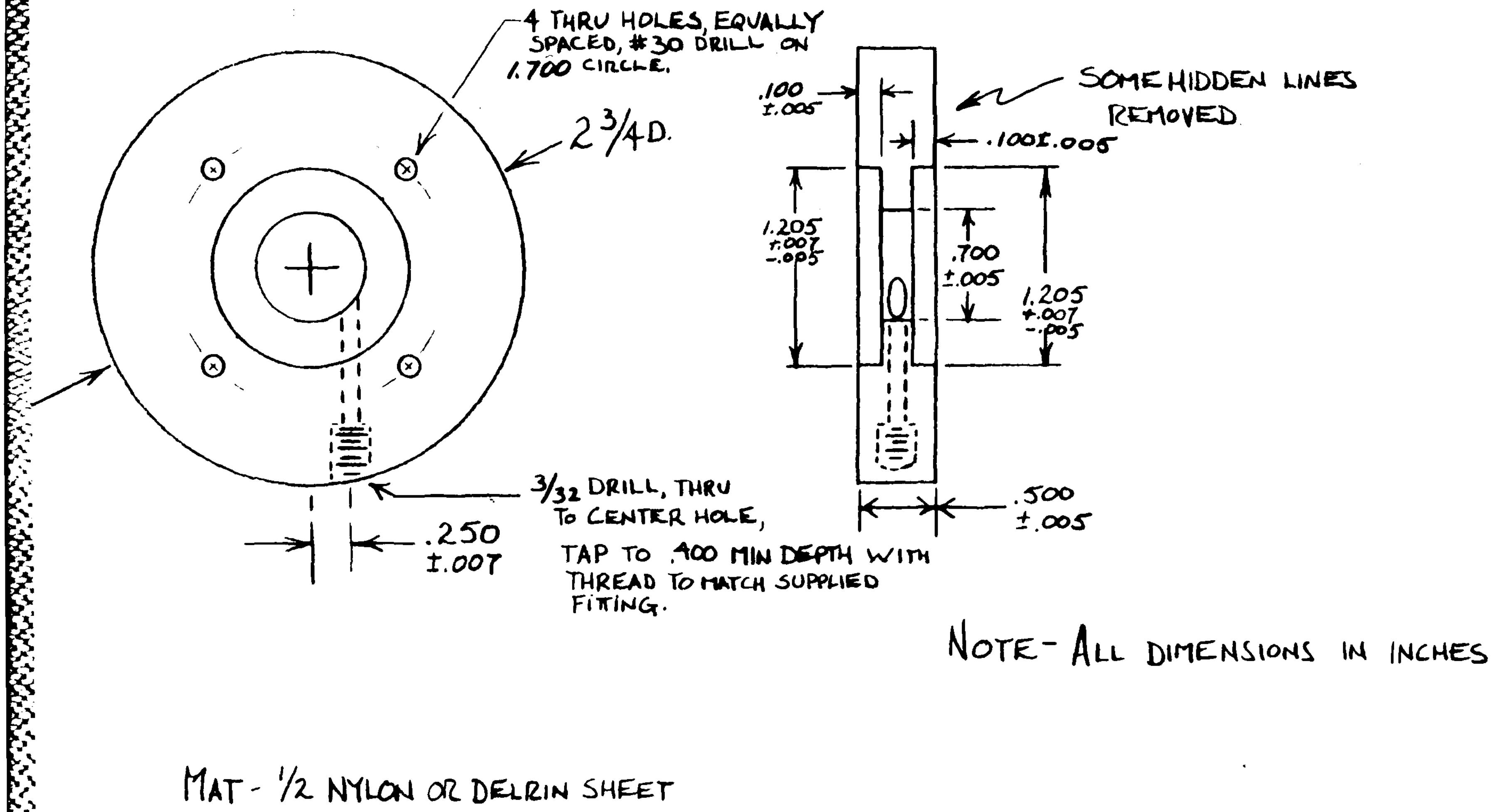
Spacer

Figure 8d



Plate

Figure 8e



Insulator

Figure 8f

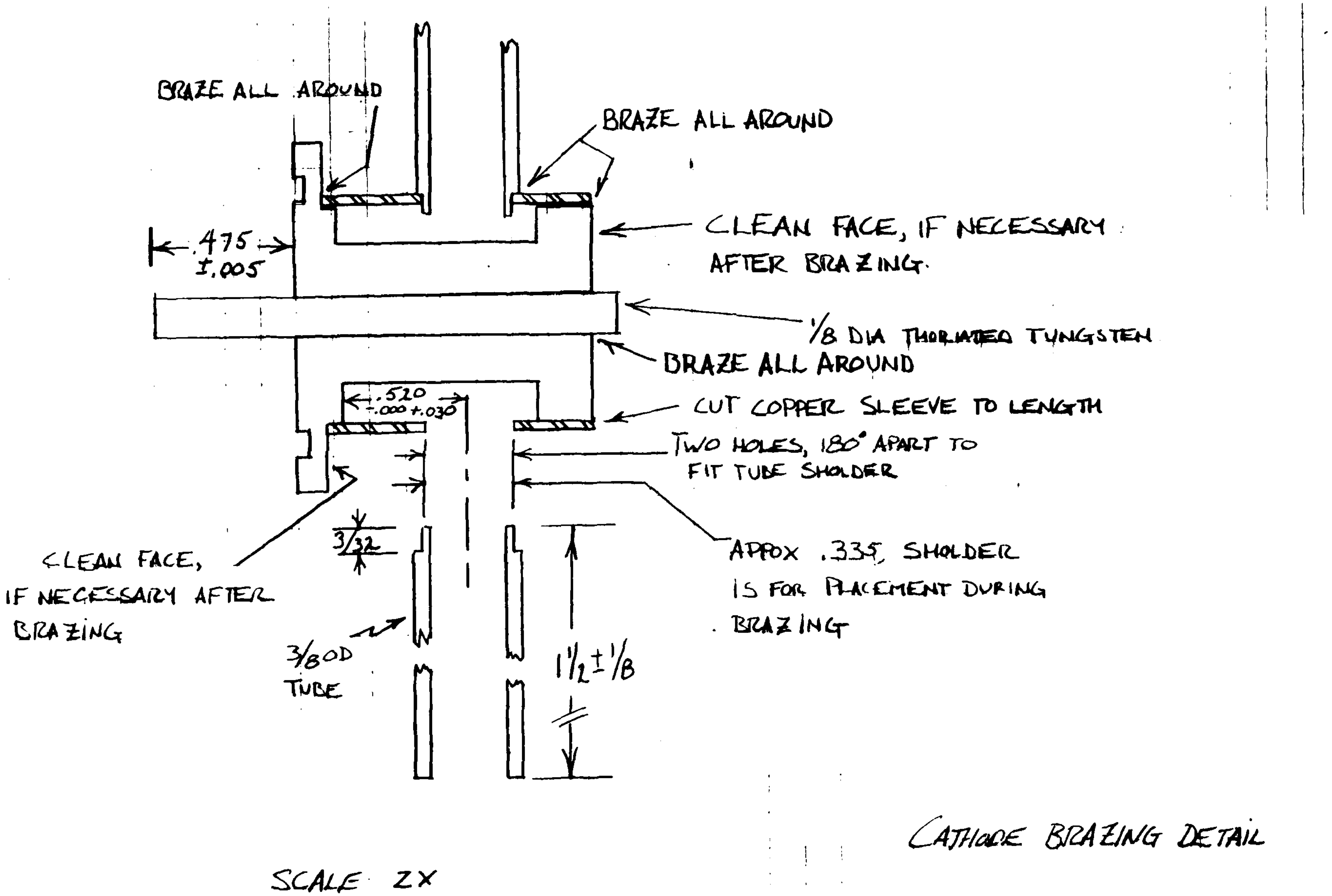
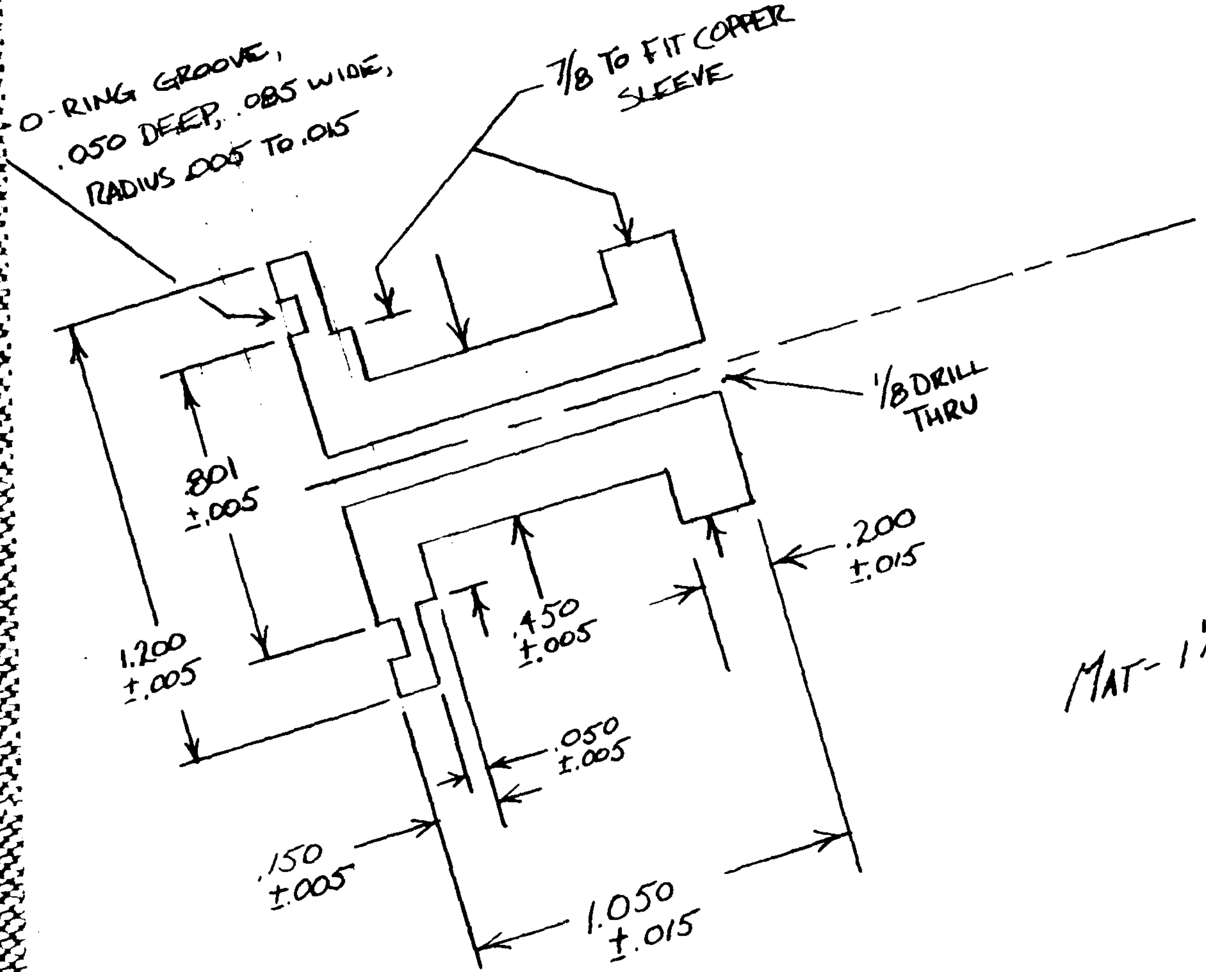

BRAZE ALL AROUND
BRAZE ALL AROUND
.475 ±.005
CLEAN FACE, IF NECESSARY AFTER BRAZING.
1/8 DIA THORIATED TUNGSTEN
BRAZE ALL AROUND
.520 -.000 +.030
CUT COPPER SLEEVE TO LENGTH
TWO HOLES, 180° APART TO FIT TUBE SHOLDER
3/32
CLEAN FACE, IF NECESSARY AFTER BRAZING
APPROX .335 SHOLDER IS FOR PLACEMENT DURING BRAZING
3/8 OD TUBE
1 1/2 ± 1/8
SCALE 2X
CATHODE BRAZING DETAIL

Figure 8g



MAT- 1 1/4" DIAMETER COPPER

CATHODE BODY

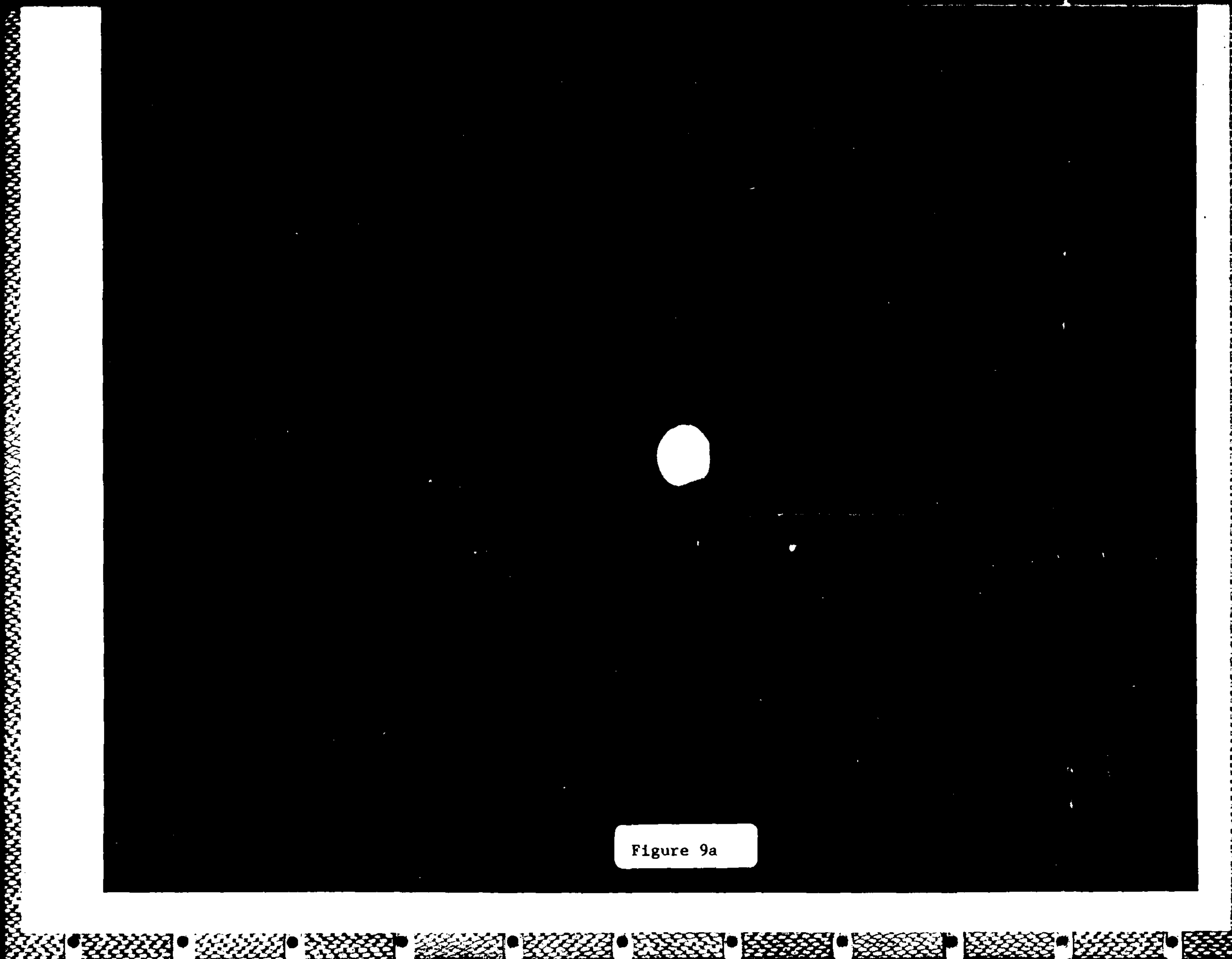


Figure 9a

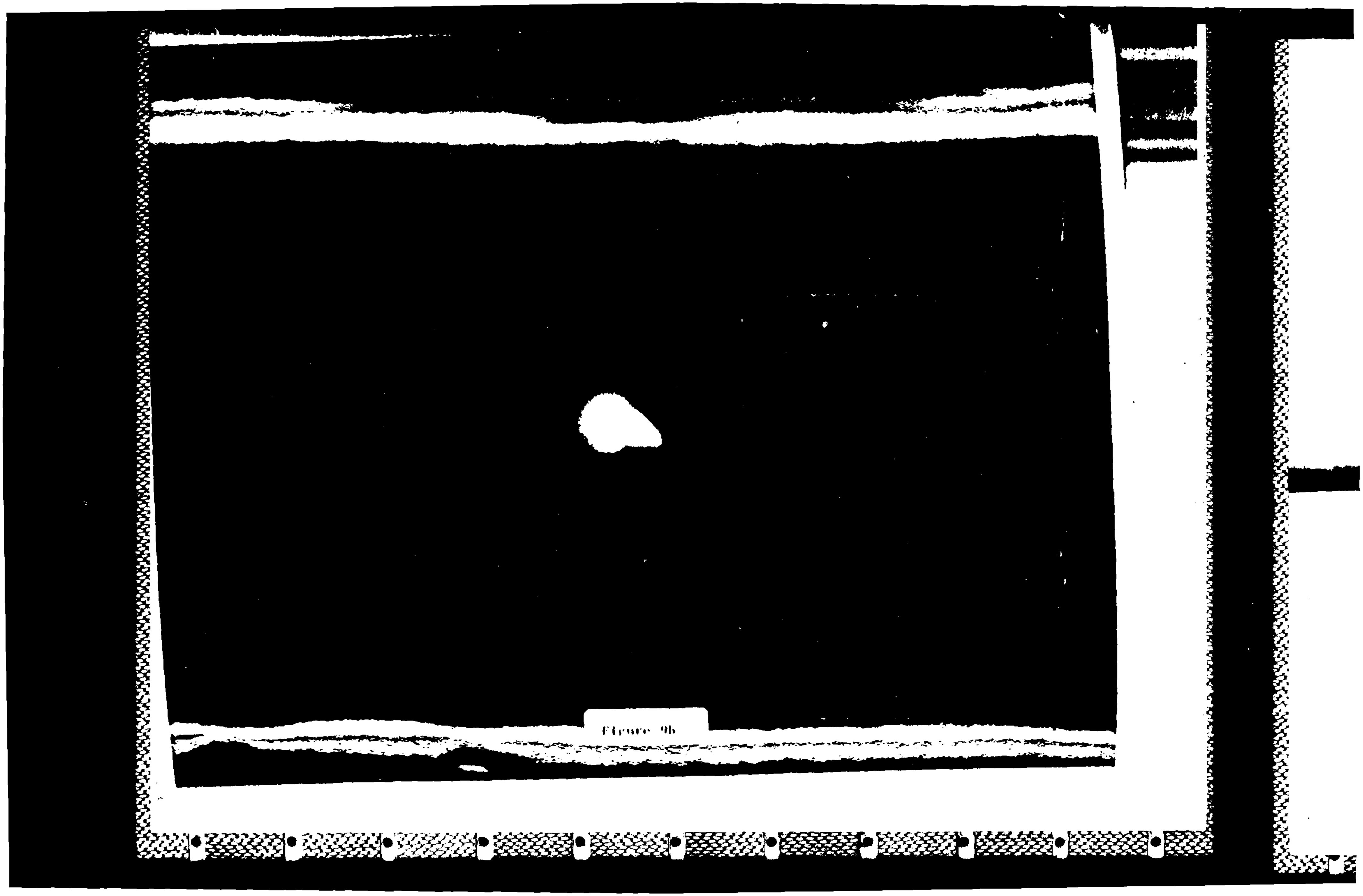


Figure 9b

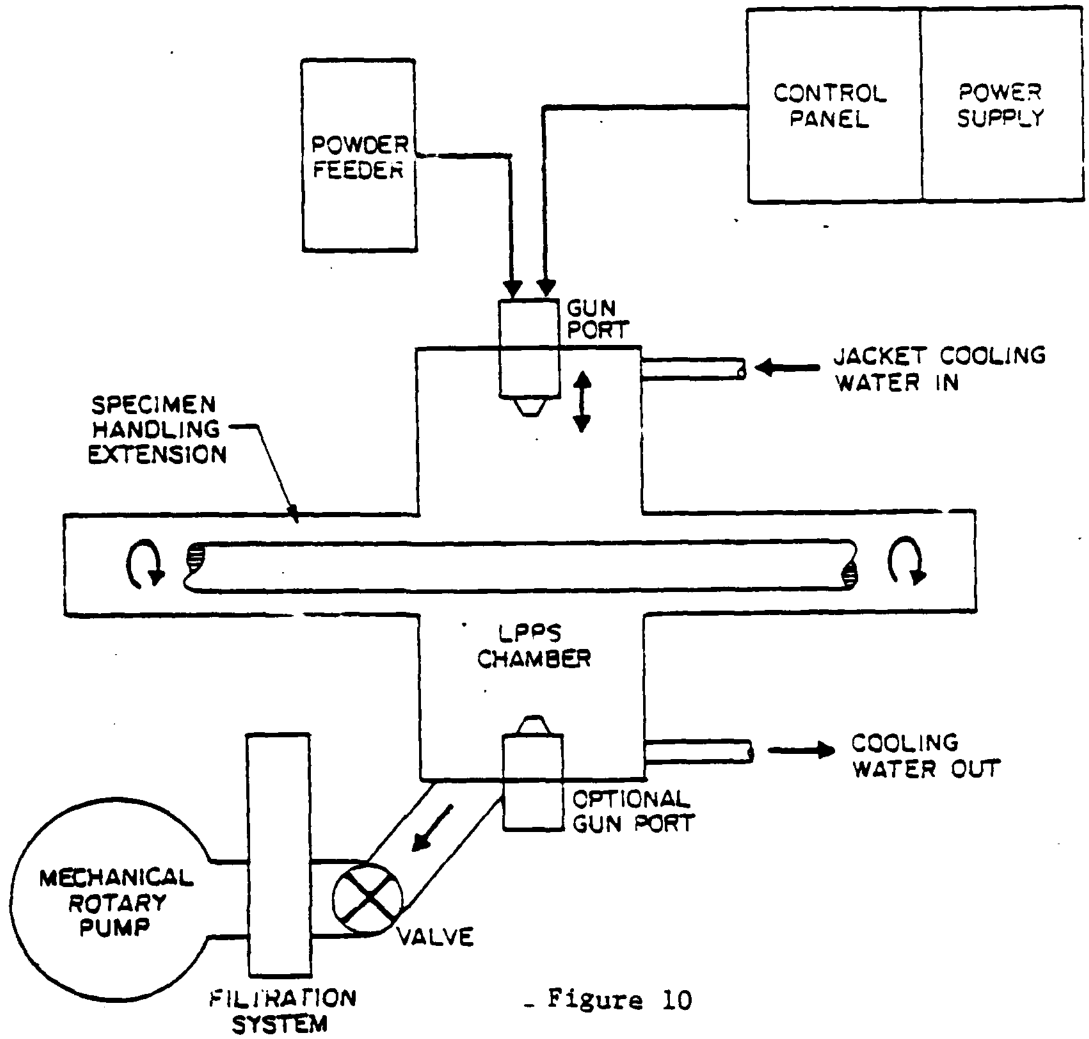

POWDER FEEDER
CONTROL PANEL
POWER SUPPLY
GUN PORT
JACKET COOLING WATER IN
SPECIMEN HANDLING EXTENSION
LPPS CHAMBER
COOLING WATER OUT
OPTIONAL GUN PORT
MECHANICAL ROTARY PUMP
VALVE
FILTRATION SYSTEM

Figure 10

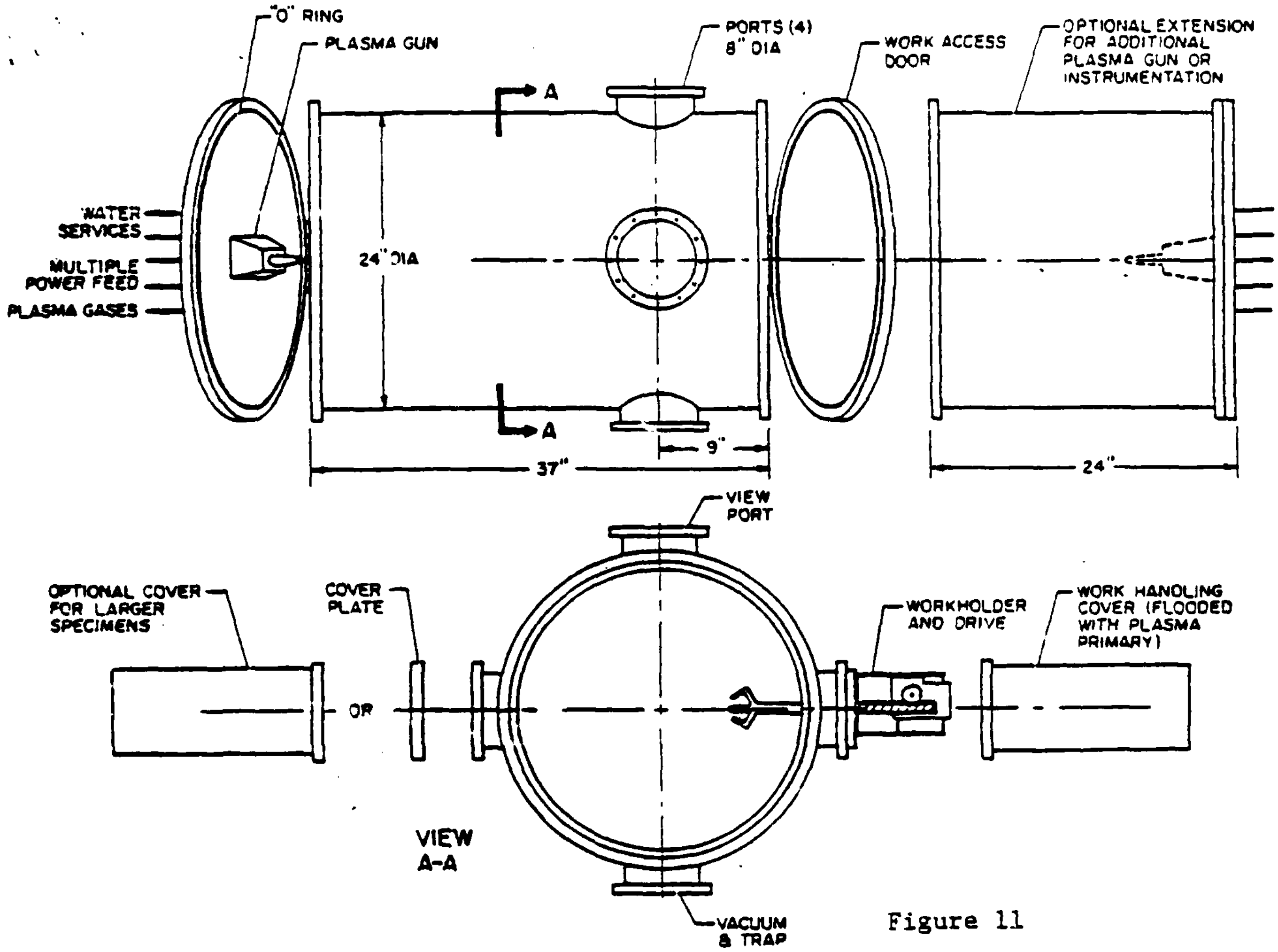
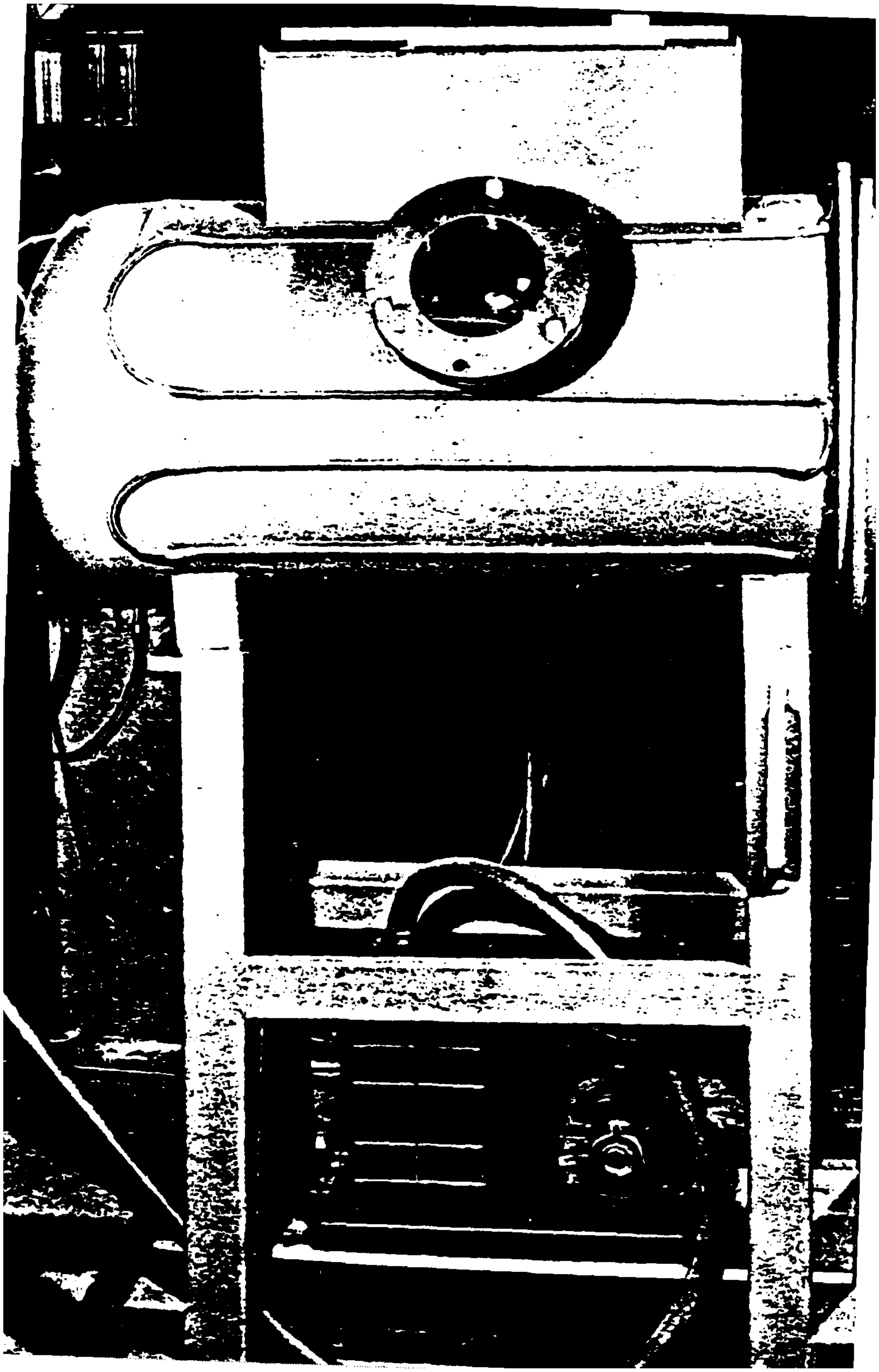
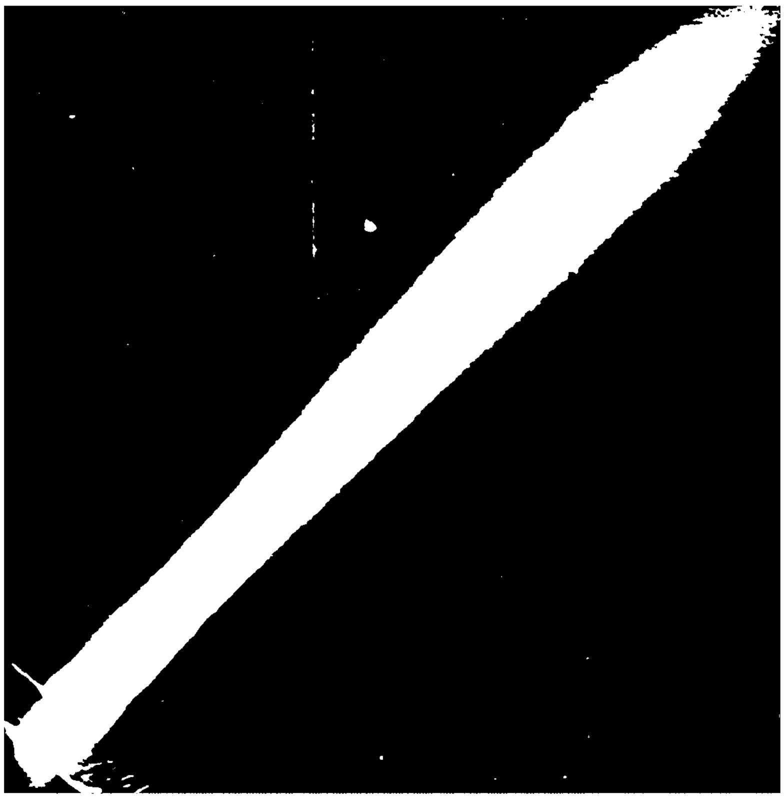

"O" RING
PLASMA GUN
PORTS (4)
8" DIA
WORK ACCESS
DOOR
OPTIONAL EXTENSION
FOR ADDITIONAL
PLASMA GUN OR
INSTRUMENTATION
WATER
SERVICES
MULTIPLE
POWER FEED
PLASMA GASES
24" DIA
A
A
9"
37"
24"
VIEW
PORT
OPTIONAL COVER
FOR LARGER
SPECIMENS
COVER
PLATE
WORKHOLDER
AND DRIVE
WORK HANDLING
COVER (FLOODED
WITH PLASMA
PRIMARY)
OR
VIEW
A-A
VACUUM
& TRAP

Figure 11

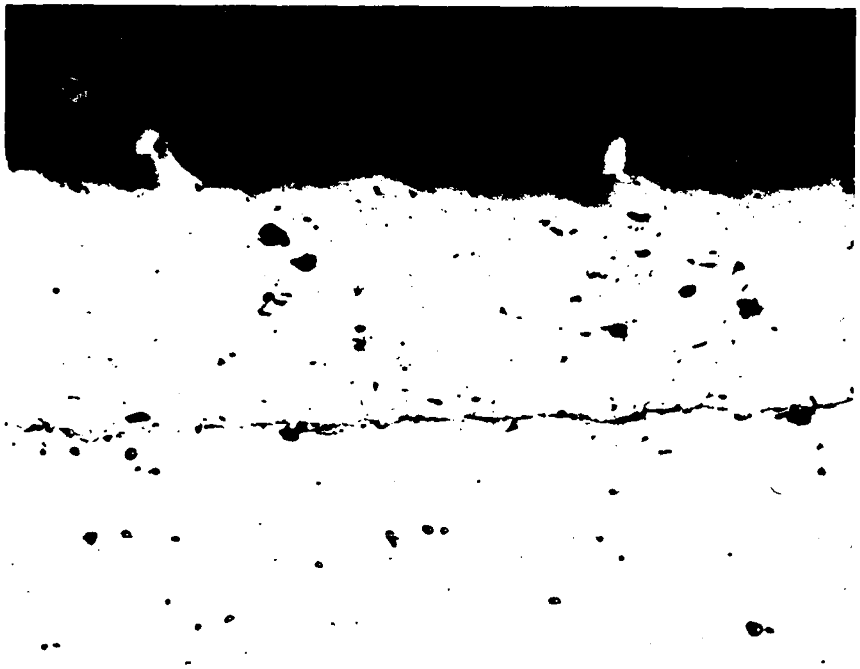




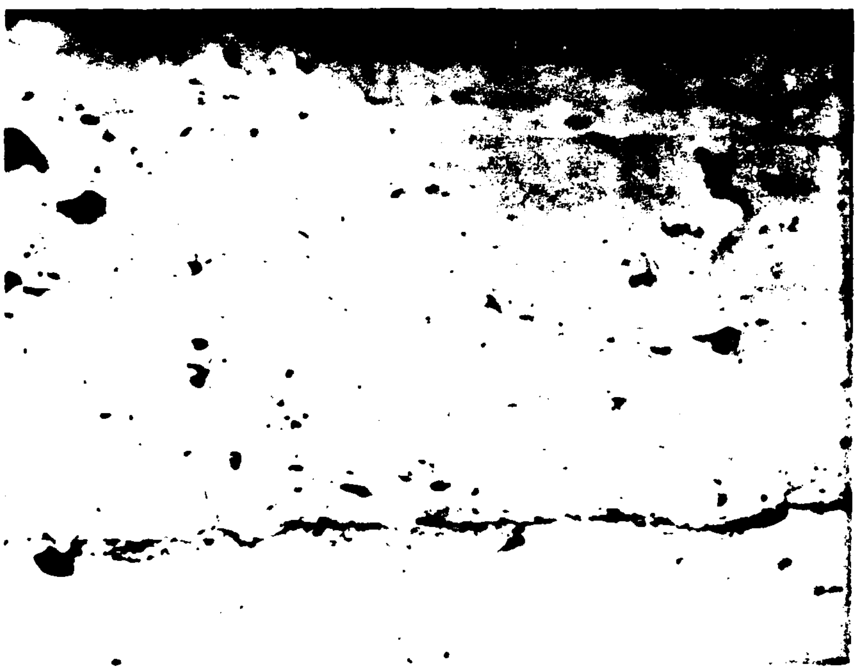
a

b

Figure 14a and b



c



d

Figure 14c and d

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